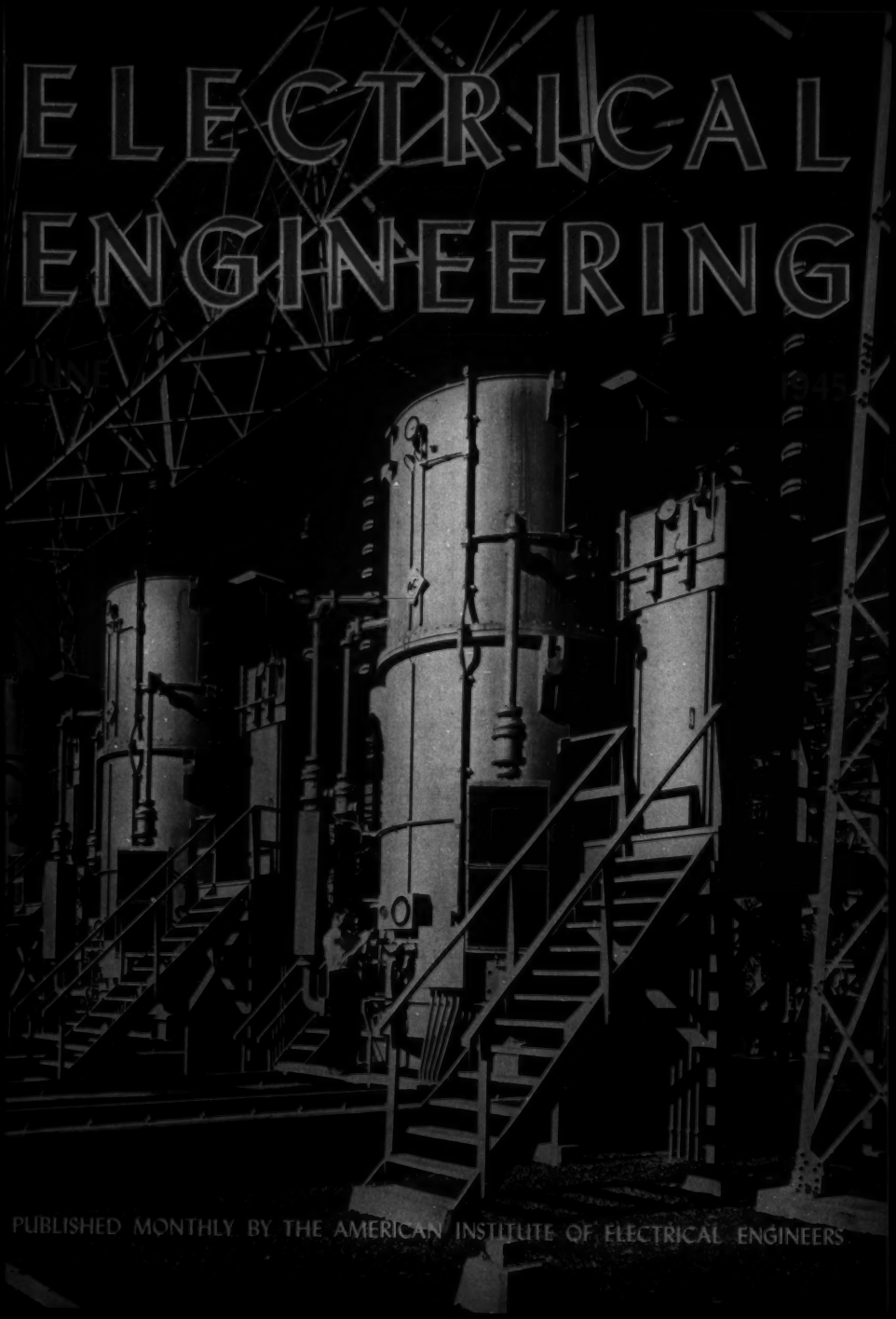
ELECTRICAL ENGINEERING



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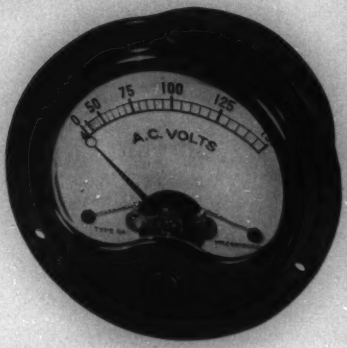
1.5" Commercial Type OD d-c Milliammeter



2.5" Commercial Type DA a-c Voltmeter, 400 cycle

New R-S Instruments—

built to Rigid Specifications

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Immersion Proof

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Commercial types of these two aircraft miniature panel instruments are built in conformity with the same exacting requirements.

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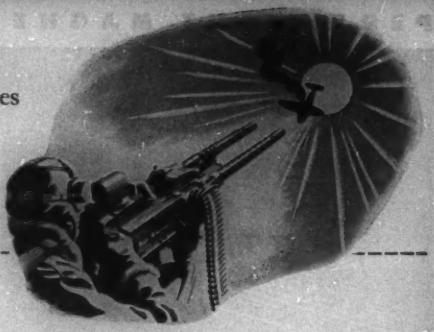
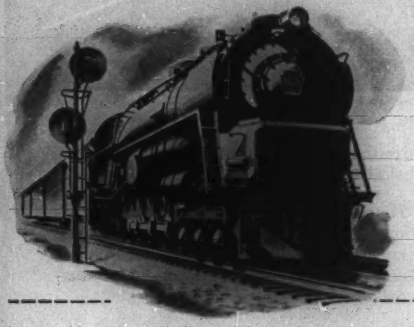
. . . the name on the GUNSIGHT LAMP is Westinghouse.





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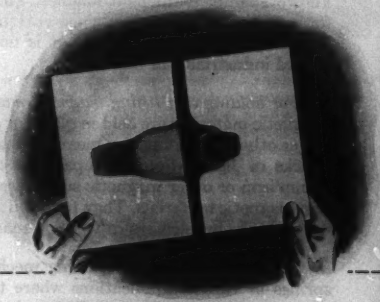
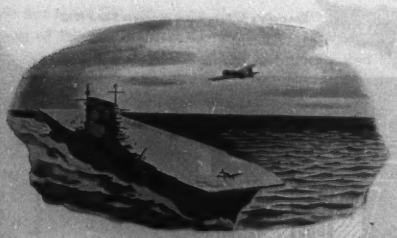
. . . the name on the X-RAY TUBE is Westinghouse.





On a carrier a PLANE DIRECTOR uses a new kind of elevator to hoist planes on deck faster — keeping the deck cleared and getting fighters into the air quicker.

. . . the name on the ELEVATOR is Westinghouse.

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TOMORROW — This same research and engineering skill will mean more dependable, more efficient industrial equipment and appliances for the home.

Tune in: JOHN CHARLES THOMAS—Sunday 2:30 pm, EWT, NBC

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PERMANENT MAGNETS MAY DO IT BETTER

(This is the third in a series of four advertisements discussing the major functions of permanent magnets)

TRACTIVE EFFORT from PERMANENT MAGNETS

The power to attract magnetic materials led to the discovery of the lodestone—the earliest known form of permanent magnet. The same force has served mankind, since antiquity, in the compass. This tractive effort is now employed industrially in three ways.

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3. *To transmit motion without mechanical connections.* Permanent magnets can reproduce motion from one part to another through a seal—as in the flow meter and other packingless drives.

Indiana Steel is the largest exclusive manufacturer of permanent magnets, established for over 35 years. Without obligation, our engineers will be pleased to consult with you on any of your problems involving their possible application. Write for copy of technical booklet: "Permanent Magnets Have Four Major Jobs."

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Specialists in Permanent Magnets Since 1910

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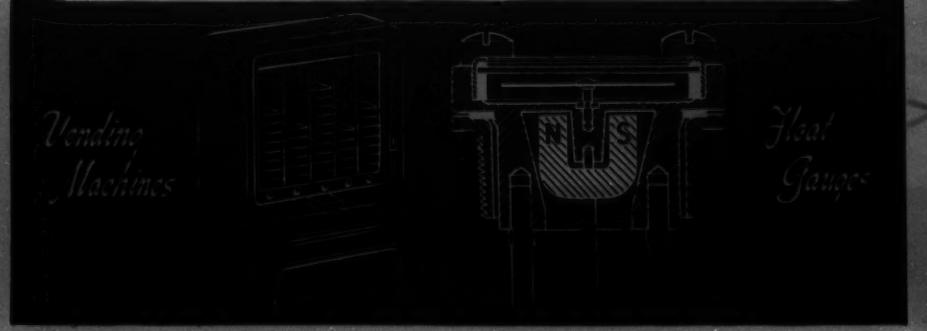
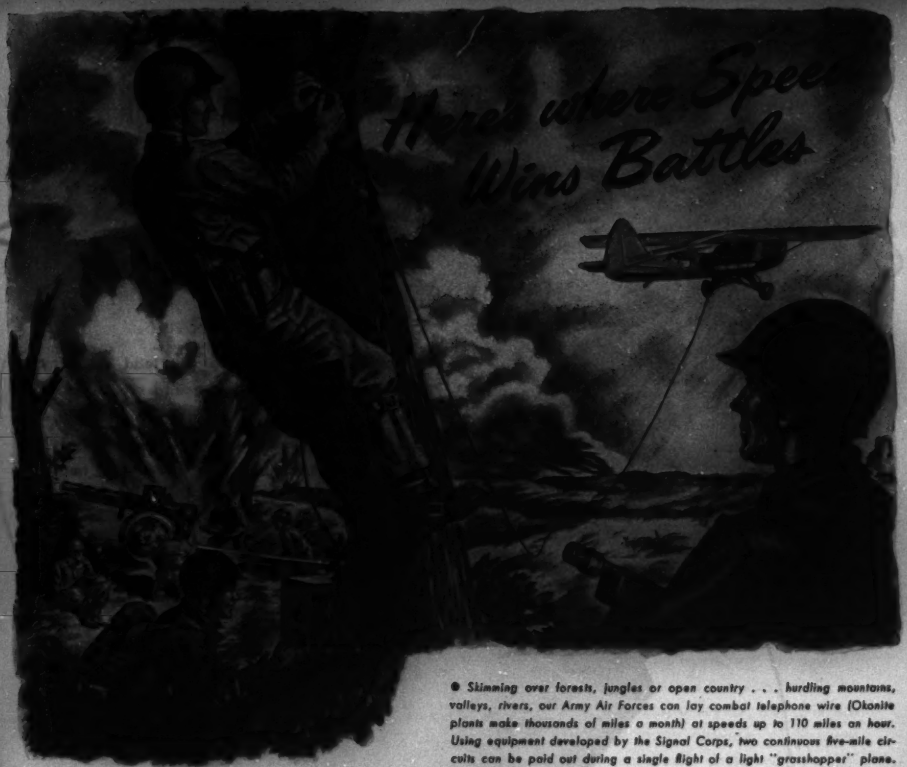


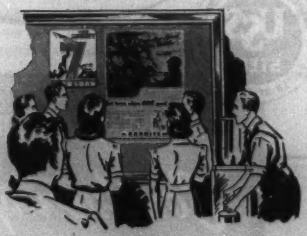


● *Skimming over forests, jungles or open country . . . hurdling mountains, valleys, rivers, our Army Air Forces can lay combat telephone wire (Okonite plants make thousands of miles a month) at speeds up to 110 miles an hour. Using equipment developed by the Signal Corps, two continuous five-mile circuits can be paid out during a single flight of a light "grasshopper" plane.*

but here's where *OUR* speed counts

● At home the 7th War Loan is on . . . one mighty effort instead of the two we had up to this time last year . . . a challenge to all of us in industry to get quickly and solidly behind our local bond drive.

Sure — it's a big job to top our quota. Everything about this war is big including our responsibility to those in uniform. Our fighters are depending on us at home to put our job over. It's the least we can do for them — and the War Bond purchase window is the place where your speed counts most now.



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insulated wires and cables including combat wire

The Okonite Company, Passaic, N. J. • Okonite-Callender Cable Co., Inc., Paterson, N. J. • Hazard Insulated Wire Works Div., Wilkes-Barre, Pa.

4081

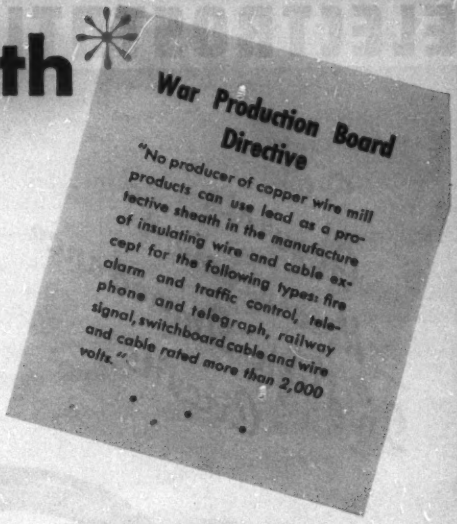
No, it isn't lead*, it's CONDUCTING

Conducting rubber replaces lead on this new power cable for underground service and results in greater flexibility, lighter weight, easier splicing, greater resistance to electrolysis and corona effects. It is less affected by heat and withstands the effects of water, acids, alkalis and oxidation.

AMERICAN STEEL & WIRE COMPANY
USS STEEL
UNITED STATES STEEL

U·S·S AMERICAN
Conducting Rubber
SHIELDED POWER CABLE

covered with RUBBER


War Production Board Directive
"No producer of copper wire mill products can use lead as a protective sheath in the manufacture of insulating wire and cable except for the following types: fire alarm and traffic control, telephone and telegraph, railway signal, switchboard cable and wire and cable rated more than 2,000 volts."

New Power Cable for underground work has many advantages superior to lead

SINCE lead can no longer be used for underground power lines rated below 2,000 volts, American Steel & Wire Company engineers have developed a new power cable sheathed in conducting rubber.

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Columbia Steel Company, San Francisco, *Pacific Coast Distributors*

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PROJECTING
FLUSH

For Accurate Measurement In High Impedance Circuits

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0- 300 Volts
0- 450 Volts
0- 600 Volts
0- 750 Volts
0-1000 Volts
0-1500 Volts
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Ferranti Electric, Ltd., Toronto, Canada · Ferranti, Ltd., Hollinwood, England

ELECTRICAL ENGINEERING

Registered United States Patent Office

JUNE
1945

The Cover: A 150,000-kva bank of 220-kv forced-oil-cooled autotransformers.
Allis-Chalmers photo

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G. Ross Henninger
Editor (on leave)
W. R. MacDonald, Jr.
Acting Editor

F. A. Norris
Business Manager
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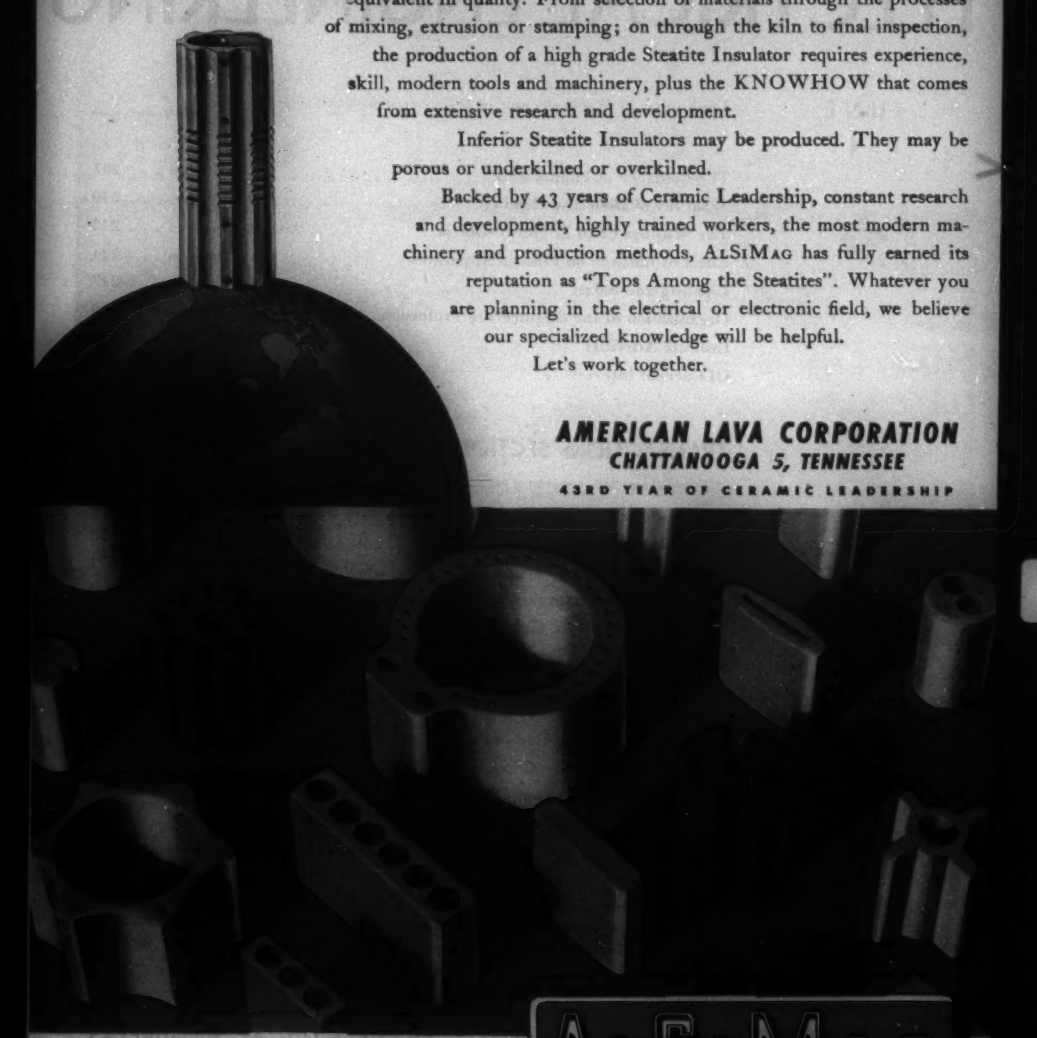

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ALCO has been awarded for the fifth time the Army-Navy "E" Award for continued excellence in quantity and quality of essential war production.

The Romance of Engineering

C. A. POWEL
PRESIDENT AIEE

THE electrical industry is nearly 70 years old and what do we find as a result of 70 years of endeavor? At the very time when we, of all people, should be pointing with pride to the achievements of our industry and looking forward to even greater opportunities, we find among our younger engineers and engineering graduates a feeling of uncertainty born of the war's tremendous crosswise forces. With it has come a question whether some form of collective bargaining arrangement might not produce a feeling of general security, despite the corollary that it would probably reduce all participants to a common denominator and diminish the chances of those with outstanding initiative and brains from making rapid progress in their chosen fields of engineering. What has happened? Is the romance of engineering so dead that material gain is the only factor of any importance? I hope not. In the closing decades of the last century, a boy would watch trains go by and yearn to become a locomotive engineer. There was something romantic about the great iron horse disappearing in the distance with its load of cars, and as the boy grew older the only change in his ideas was the preference for an engineering and design activity rather than one of actual operation.

That was the steam age and various improved forms of reciprocating engines were being developed—the big slow-speed Corliss valve engines for rope drive weighing up to 600 tons. Then various designs were made of lighter high-speed high-pressure engines—high pressure meaning up to 200 pounds—notable among them being the Willans cylindrical slide-valve engine, which continued into our day in the form of the Knight internal combustion engine. It was the most economical engine of its day but was displaced by the more efficient high-speed poppet-valve engine. All these finally gave way to the steam turbine at about the time electricity was really taking hold.

Electricity was the great new industry with untold possibilities but with many unsolved problems. We all got into it—everything was new and interesting and full of promise. Actually, of course, it was not new—it just seemed new to us youngsters. I have no doubt that Doctor Gilbert got just as much of a thrill from his experiments with frog legs and Benjamin Franklin with kites and his attempts to electrocute turkeys as we did in designing transformers. When I was in school, we still thought there was merit in designing three-phase transformers with the cores arranged physically 120 degrees apart. The yokes, top and bottom, had nice concave curves and the whole thing was in a round tank. About that time the first large turbogenerators, 2,000 to 5,000 kw, were designed and transmission lines up to 50,000 volts. There were no convenient Nesbit tables, and we had a lot of fun calculating reactance and capacitance effects from fundamental equations. Main-line railway electrification was just getting under way, single-phase in the United States and three-phase in Europe.

Many unsolved problems that await the initiative, ingenuity, and industry of the young and up-and-coming engineer are outlined in this paper. Here, also, is a plea to make the engineering profession attractive enough to appeal to the best students. A kaleidoscopic view is presented of the progress in electrical engineering over the past 70 years.

Have things changed? Of course, they have. The rate of change in human affairs has reached a terrifying pace. The history of civilization is the history of power and technical development. Originally, all that was available was man power and as it took man all his time and energy to keep alive, what we know as civilization was nonexistent. But as he learned to apply the lever and animal power, then wind power and water power, his lot improved and he found himself with leisure time, and with it came the development of civilization. We do not know how long it took man to reach the wind- and water-power stages, which are first mentioned in records of 150 B.C., but it was certainly hundreds of centuries. Another 12 or 15 centuries effected the breaking up of feudalism and another two or three centuries bring us to the industrial revolution and from then on civilization developed rapidly and we have to count time not in centuries but in decades.

One of the criterions of the advance made through the centuries is the power developed and placed at the disposal of man. In the United States, 200 billion kilowatt-hours of electrical energy was sold in 1944, the equivalent of 550 million kilowatt-hours per day. If it be assumed that one third to one half of this represents useful work, we obtain 200 million kilowatt-hours of actual work done per day. Now a man can perform about 150 watt-hours of useful work in an eight-hour day, so that the output of the electrical industry in this country is equivalent to the work of $1^1/_4$ billion slaves working eight hours, seven days a week; or ten slaves for every man, woman, and child in the country. But the electrical industry accounts for only $^1/_{40}$ of all the energy consumed in the United States, so that we get 400 as the number of slaves at the beck and call of every one of us in this country. Fantastic as these figures are, they go a long way toward explaining the difference in our present-day standard of living as contrasted with that of even the elite of ancient Egypt. Had the Nazis and Japs pondered such figures, perhaps they would have hesitated before unleashing such fury as this power represents.

Changes in the social system no doubt always have seemed rapid to those who lived through them, but looking back we see a rate of acceleration which shows no signs of letting down. Changes are going on at a continually increasing rate. Something that was new and novel ten years ago is antiquated today, as witness developments in radio and aviation. Can any system that is accelerating at an increasing rate of change be stable? As engineers, you will answer: "No, before long something has to explode"—and maybe things have exploded. Certainly in the last 25 years we have had more than enough "noble experiments" on how to influence human behavior—communism,

Essential substance of the presidential address delivered at a meeting of the AIEE New York Section on April 10, 1945.

fascism, Prohibition, New Deal, and now a promise of planned economy. It would seem that it is time to settle down to some sane and safe system, but can we? All around us we sense fear—fear of inflation, fear of regimentation, fear of government ownership of industries, fear of loss of individualism—not necessarily as a result of the particular administration we happen to have at the moment, but because of world trends. Everywhere we see the growing power of governments with the tremendous, and in some cases manifestly absurd, increase in the number of bureaus and their personnel. It is interesting to note in passing that among the indictments which the framers of the Declaration of Independence drew against George III was one reading: "He has erected a multitude of new offices and sent hither swarms of officers to harass our people and eat out their substance."

There is, however, one important factor from which we can take comfort and build a strong hope that present tendencies will not reach the point where they do permanent harm to our system of government and free enterprise. Democracy, as practiced in this country and one or two others, is essentially a continuous struggle between competing groups. For a period of time one group gets the upper hand, then another; but corrective measures always develop to prevent any group from causing permanent injury to another group. There are two ways in which this process may cease to function—one is a resort to arms by the ruling group, as was demonstrated in Russia, Italy, Germany, and Spain, and the other is a cessation of fighting by the opposition and an acceptance of everything that is imposed upon it. The first is unthinkable in this country. The second must not be permitted to happen. As the late Wendell Willkie so forcefully pointed out, we must have an opposition not merely for a month or two before election time, but for all time. Only so can we prevent the fruition of such peculiar ideas as are embodied in the Kilgore Bill socializing research and in other bills recently proposed.

The reason I bring these matters up is that they are of great importance to our Institute. We are dependent for our continued success on students—not any students, but the best students. Anything that tends to discourage boys and lead them to seek a livelihood elsewhere hurts us. If they are led to believe that electrical engineering is static and that all they can hope for is a routine job under conditions made tolerable for them by some labor union and a few government bureaus, they will certainly drift into other lines of endeavor. We can keep the best boys in the electrical schools only if we can show them that the profession offers them a future as a profession, where they can develop their native talents and rise to higher levels than their less-gifted contemporaries.

What are the prospects today in electrical engineering? There are, of course, the still unknown fields in the application of electronic tubes; in the application of radar and ultra high-frequency technique, but even in the old low-frequency power field, nowhere do we find a static condition. For the last 15 years it has seemed that the ultimate had been reached in transformer design and efficiency, and yet transformers continue to get smaller and more efficient. The same can be said of turbine-generators, so why should we assume that a limit has been reached as long as improvements in our fundamental materials—insulation, iron, copper, and their alloys—are possible.

Let us look at that pioneer of the electrical industry—insulation. The earliest insulation material on record is silk. Then came cotton, oil, rubber, paper, mica. The story of insulating materials is a fascinating one in itself. For instance, paper so widely used today was of little use until the technique of proper selection and preparation of wood pulp to remove conducting impurities and lignins was developed to produce almost pure cellulose fibers. Then came improved processes to reduce its thickness; treatment with synthetic resins to obtain high dielectric constant, and so on—a story of continuous improvement. But all these materials had one thing in common. They were all organic or required organic bonds.

Now after 70 years the electrical engineer is finally presented with something entirely new—the silicones—which will stand temperatures undreamed of with our old organic materials. The silicones are made from sand, salt, coal and oil, all plentiful and native to our country. They form a new family midway between glass and plastics and have remarkable characteristics. For instance, in one form, the silicones resemble putty and can be kneaded like putty, but unlike putty, they bounce like rubber balls. Silicone liquids can be chilled to 100 degrees Fahrenheit below zero without freezing and heated to 350 degrees Fahrenheit above zero without boiling. The silicones are of interest to the electrical engineer because they can be made into a bond—an inorganic bond—for glass and asbestos to produce a very high temperature insulation. And does the engineer know what to do with this new insulation? Will it revolutionize the design of electrical machinery? As yet there is no evidence to that effect, but one would be rash indeed to take a positive stand. There are, of course, some obvious applications, such as motors in locations with very hot ambient temperatures, certain traction motors, air-cooled transformers, and so on. It is certain that our young engineers will find many other applications—not necessarily those working in the research laboratories, but the young men recently out of college who are in the design departments and engineering laboratories.

As another example, let us look at high-frequency heating. Its characteristic advantages are (1) rapid and readily controlled rates of heating, and (2) the ability to create heat within the material itself or to confine it to the surface only. These advantages are so outstanding that at first sight it would seem this method would soon replace all the old methods, where heat has to be created outside and forced into the place where it is needed. But, after all, heating, like all other processes, must obey economic laws. Therefore, at present it is not universally applicable, but no one can doubt that its field of application will be tremendously enlarged when our young engineers get on the job and find ways and means of cutting the costs. Imagine, for instance, a rolling mill without any gas-fired furnaces, the slabs to be rolled into strip simply being passed through a high-frequency magnetic field ahead of the first rolls and heated electrically. When rolling ceases, the switch is pulled and the whole operation is dead until the next slabs are ready.

Dielectric heating, in which heat is created within non-conducting materials, has been used to some extent in the production of plywood, to cure plastics and so on, but here too is a wide-open field for the young engineer with imagination.

Lightning and lightning phenomena have always caught the public fancy and one would expect by this time that the last word had been said about them. Only a few years ago transmission engineers were told that lightning was an act of God that would knock their lines out of service and not much could be done about it. In the last 15 years progress has been made through the work of many engineers to the point where lightning is kept well under control and lightning-proof high-voltage transmission lines can be built. But is the job finished? By no means. There remains much to be done, particularly in the solution of the lightning problem in the subtransmission and distribution fields. Only when protection has attained somewhere near 100 per cent effectiveness should efforts along this line be eased.

There are still many questions unsolved concerning the build-up and the distribution of the charge within the cloud. Also, we need to know more about the mechanism of propagation of the stroke, and the effect of resistivity of the earth upon it. These phenomena have a large effect upon the rate of rise of stroke current and the voltage produced on the line. We also need greater knowledge concerning the deionization characteristics of the stroke channel.

Even the mathematically minded young engineer need not despair of an opportunity for the application of his talents. Basically all electrical science stems from

the fundamental equations developed by Maxwell. Since his time the efforts of the analyst have been devoted to means for solving these equations. For years a-c problems were solved empirically until the application of complex numbers to their solution. The solution of polyphase problems was restricted almost exclusively to single-phase equivalents until the development of symmetrical components by Fortescue.

And yet in spite of the enormous progress represented by the foregoing treatments, only a limited number of our problems lend themselves to rigorous analysis. Complicated power systems have been set up in miniature on d-c and a-c calculating boards for the solution of such problems as system short circuits, stability, and voltage regulation. Transient solutions have been attacked likewise through setting up the system in miniature, applying the discontinuity cyclically by means of a commutator and observing the results with the help of an oscilloscope. This idea can be extended to the solution of mechanical problems. In this field it is particularly valuable because of the difficulty of measurement of mechanical quantities when an attempt is made to represent the mechanical system by means of a mechanical miniature of the real system. These tools offer enormous possibilities to the electrical and mechanical engineer in the solution of the problems that are bound to confront him. The method has only just been started. As developments proceed, the need for accurate solutions becomes more and more imperative; who can tell what further developments in the field of analysis are open to the engineer of the future.

A large group of apparatus involves for its operation commutation or interruption of current. Thus the ideal is conduction of current with zero voltage drop at one instant, and nonconduction at the next instant. If the transition between these can occur in zero time, no loss occurs in the equipment. In a sense this ideal operation can be viewed as a condition in which the apparatus is called upon to do no work, for during the conduction period the voltage drop is zero and during the nonconducting period the current is zero. Circuit breakers, lightning arresters, and rectifiers of all kinds fall within this category. Thus, if a circuit breaker could be so designed that the arc path would deionize completely at the instant current normally passes through zero, the apparatus would fall within the class just discussed. To the extent that the arc drop is not zero and the arc path does not convert instantly to infinite impedance is the measure by which the breaker departs from ideal, and this sums up the effort of design engineers of circuit breakers. They have not attained this ideal and are still striving to approach it. Some 20 years ago the oil circuit breaker had an opening time of the order of a second. Today we have eight-cycle, five-cycle, and three-cycle breakers. Presumably the utility engineer will not be happy until he gets a one-cycle breaker, and, who knows, maybe some young engineer not yet out of school will produce it for him, by working on an entirely different type of interrupting device and other mediums of interruption.

In the field of rectification there has been the development of the multi-anode rectifier and the ignitron in the larger ratings and the thyratron and copper-oxide and selenium rectifiers in the smaller sizes. Copper-oxide and selenium rectifiers have a marked advantage in life and maintenance over other types. The progress in the development of these types of rectifier has been enormous. They have been used in units up to 100,000 volts at small currents and as high as 60,000 amperes at low voltage. There is no reason to believe that we have reached the limit of perfection in these devices. Perhaps some day these devices or one of similar characteristics might be developed that could be grid-controlled. Such development would open vistas of applications now untouched.

A substantial amount of all engineering progress is based on taking advantage of radical improvements in existing tools. Capacitors offer a good illustration of this. The advances in the capacitor art have made possible a wide use of equipment which was impractical only a few years ago. Although the capacitor is one of the oldest electrical devices, dating back to the Leyden jar, its use was restricted until 20 years ago because it was available only in very small sizes. In 1924 the need for correcting system power-factor and the great demand for capacitors for the radio industry resulted in constant improvements in capacitor materials and design, so that at the present time the cost per kva of capacitors is only 15 to 20 per cent of the cost in 1924. In that year, when large power-type capacitors first became available, their use was limited to correcting low power-factor in industrial plants. Today their low cost and small physical size per kva make practical energy-storage welding, great advances in inductive heating, polyphase motor performance on single-phase supply, electrical precipitation, and hundreds of other devices. The use of series capacitors to increase the power carried over a transmission line has intrigued engineers for many years, but still awaits practical application—a nice problem for some up-and-coming young engineer. Capacitors are a necessary adjunct of many new electronic devices and in the hands of a creative young engineer their field of application is practically unlimited.

Many more examples, such as those cited, could be added in the power field not to mention the communication and transportation industries. The land of opportunity in the minds of the public lies in chemistry and aviation. These provide the new and spectacular developments and they receive wide publicity just as electric lighting and the electric motor did in the early years of this century. They represent the unknown where the explorer can search to his heart's content. But does this picture represent the facts or is it just the present attitude of mind? Does not the biggest opportunity come in the fields already developed where a small percentage in growth means hundreds of times what it amounted to when the industry was young?

A little reflection will show that this is so. Our industry is far from static and it is not necessary to go into the research laboratories for the solution of new problems. Our methods of power generation, transmission, and distribution are still far from perfect. The application of electricity to heavy industries, to the marine industry, to aviation, to medicine, to the food industry, is still in its childhood. Under free enterprise it can continue to grow and to offer not only a livelihood to the best of our young men, but also a great opportunity for creative and original work. The postwar period will open up a demand for equipment of all kinds. Many of the devices developed specifically for war purposes will be adapted to peace-time uses. An example of this is the tank-gun stabilizer invented by Doctor Hanna and used on all American tanks to keep the gun pointed on the target despite the jolting of the tank over rough ground. This stabilizer may well find application to railroad cars and perhaps to automobiles to provide smooth riding over bumpy rails and roads.

The greatly expanded use of various types of vacuum tubes during the war is bound to have its effect on postwar engineering. We are becoming more vacuum tube conscious. Military applications will familiarize many young men with the possibilities and characteristics of these Pandora devices. No longer can the tube be looked upon as a delicate laboratory device. Too many have had to withstand the severe Navy shock-test, and have gone through actual combat experience to permit any idea of their fragility to persist.

Even the political and economic developments brought about by the war are bound to have some impact on engineering practice and industrial development, resulting in engineering problems of design and production which will call for plenty of ingenuity on the part of the young engineer. We must see to it that he is allowed a free hand to apply his talents. A certain amount of government regulation is probably necessary and desirable, but not regimentation. There is a great difference between them. Regulation is being told what one may not do—the old German "verboten" which used to cause us much amusement. Regimentation is being told what one can and must do. This is the new tendency of all

governments which must be broken down if democracy and free enterprise are to survive. Engineering and scientific progress grew with individual enterprise. Not until the feudal system and various forms of restrictive governments were broken down did science make any headway, and then only in those countries which permitted free enterprise. Planned economy, which is a far step toward fascism can only stifle progress and the less we have of it, the better off we shall be.

Thus, under free enterprise let us go forward, so that 70 years hence, another president of AIEE may acknowledge our accomplishments and developments without which his generation of engineers could not have progressed.

A Survey of Dielectric Heating

M. J. MAIERS
ASSOCIATE AIEE

Materials that are poor conductors of electricity may be heated electrically by subjecting them to electrostatic fields that reverse at rates of from 3 to 30 megacycles per second. The applications made so far of this form of heating promise new, improved products in the future.

ONE of the many pleasant things to anticipate in the postwar era is the prospect that some of the fundamental physical concepts learned in the World War I era may be up for re-examination, expansion, and possible modification. With radar, beams, supersonics, high frequency, and ultrahigh frequency, to mention just a few electronic terms, becoming commonplace in our vocabulary, a survey of the progress made in adapting these new tools to the tasks of industry is appropriate. This article is concerned with one of these fields of electronic application, that of dielectric heating by high-frequency methods, also sometimes known as electrostatic heating.

Prior to the development of this new tool, materials commonly were classified as conductors or nonconductors in accordance with their electric conductivity. In general, the metals and some liquids were good to excellent conductors and most gases and nonmetallic solids were considered poor or nonconductors. Those with the poorest electric conductivity were used as insulators.

The thermal properties of materials seemed to parallel their electric properties; those with good electric conductivity also in general have good thermal conductivity, and those of poor electric conductivity and thus classed as electrical insulators in general are also poor conductors of heat.

Prior to the advent of dielectric heating, the only means of heating a mass of low-thermal-conductivity material was by conduction from the outside. The result always has been a temperature gradient from the outside toward the center with the possibility of reaching uniformity of temperature throughout the mass a mathematical one only. The time required to reach a certain internal temperature is a function of the temperature gradient and the specific thermal conductivity of the material and cannot under any circumstance be altered or hastened, as surface temperatures may not be raised beyond the char point of the material.

Dielectric heating consists essentially of using the material to be heated as the dielectric of the capacitor of a resonant oscillating circuit. The frequencies commonly employed are in the range of from 3 to 30 megacycles. The heating of the material may be considered as due to molecular hysteresis or friction as the molecules are alternately charged in opposite directions. The higher the potential between the plates of the capacitor the greater the density of the dielectric fields and the greater the force exerted on the molecules; similarly, the higher the frequency at a fixed potential the greater the heating in a given time.

For practical purposes the material to be heated may be considered as electrically conducting. It is then necessary only to know the weight and specific heat of the material, and the time interval desired to bring it up to temperature. This translated into Btu determines the rate at which electric energy must be dissipated within the material to produce the desired heating. Adjustment of the voltage and frequency to bring about this rate of energy dissipation, with the proper shape of the capacitor plates in relation to the shape of the material to be heated, results in uniform heating of the material throughout its mass.

APPLICATIONS

Cereal Grains and Products. One of the first experimental applications of dielectric heating was in the field of extermination of weevils which infest cereal grains in a whole or ground state. The grain or flour was passed between the plates at a rate which would permit a temperature rise to about 140 degrees Fahrenheit. The application was successful, but the cost was such that it has not been applied to date on a commercial basis. Since that time packaged cereal products have been sterilized successfully and economically after sealing.

Plywood Manufacture. In the manufacture of plywood of the standard commercial quality generally known before the present war, thin wood laminations were coated with animal glue and pressed between steam-heated surfaces at 100 to 200 pounds per square inch. Approximately three to four inches was the practical limit of wood thickness between heated surfaces and the drying time was of the order of two to four hours depending upon the grade of wood and adhesive and the quality desired.

With the advent of resinous thermosetting adhesives, moistureproof plywood became a possibility. To obtain full strength and durability required uniform heating and cure, which consumed more time and limited output just when greatly increased output was of critical importance. A dielectric-heating unit of 300 kw was found to be suitable for standard four-foot-wide sheets of from 8 to 12 feet in length. By placing one electrode at the center of the stack and using the metal top and bottom surfaces of the press as the other polarity, stacks of plywood of any thickness up to the capacity of the press are heated uniformly to the desired adhesive curing temperature in from 12 to 15 minutes. The result has been an increase in output from the presses installed of approximately six- to tenfold and a product which has made *PT* boats and wooden assault craft possible. It has also pointed the way for a new unlimited future for the plywood and lumber industry. For us it promises permanent plywood which should be in enormous demand immediately after the war.

Essential substance of a paper presented at the National Electronics Conference, Chicago, Ill., October 5–7, 1944.

R. J. Maiers is supervisor, sales promotion division, electricity sales, Commonwealth Edison Company, Chicago, Ill.

Laminated Wood Spars and Beams. Following the same procedure as in the thinply assembly and curing, thicker sections of lumber were assembled and fabricated by pressure and heat for airplane propellers, spars, and struts, and for construction beams and construction members of various cross sections and shapes up to 12 by 24 inches and up to 60 feet in length. Another laminated lumber plank two inches thick, four feet wide, and 8 to 12 feet long is a standard item for amphibious landing parties. It is shipped piled flat and assembled aboard the ships off shore into supply tanks or rafts. These are loaded and lifted overboard and allowed to drift toward shore. Tugs and outboard pushers herd them into groups and push them up the beach. Here they are taken apart and the lumber used for building floors of barracks and warehouses.

Complete Plywood Airplane. An airplane constructed of plywood was conceived and developed using forms of heat other than dielectric heating for heating and curing the resin adhesives and saturants. However, dielectric heating is supplementing the other forms of heat in the difficult phases of assembly and has made possible the development of laminates of unusual strength for critical sections of the fuselage and wing.

Compreg Wood. Another development in the wood field is the saturating of wood with resin. The stack is then compressed to about one-half thickness at pressures of 1,500 to 3,000 pounds per square inch, and simultaneously cured by dielectric heating. The result is a dense wood which has the strength of steel and a surface requiring no other finish, and which can be machined and polished.

Other Plastic Laminates. Other laminates of paper, asbestos, felt, cotton, or woven glass are made with various resins under a number of conditions of pressure to produce materials having a wide variety of characteristics, some of them excelling aluminum and steel.

Preheating Plastic Preforms. The preheating of preforms for compression or transfer molding of thermosetting plastics by dielectric heating has been of inestimable benefit by:

(*a*). Improving quality to maximum by perfect curing.

(*b*). Speeding production of a given press.

(*c*). Permitting timed optimum predictable results.

(*d*). Reducing molding pressures necessary by 50 to 70 per cent.

The curing time for large molded parts has, in some instances, been reduced from 30 minutes to 2 minutes. Dielectric heat has completely absorbed this field.

Rubber. Blocks of rubber of practically any size can be uniformly heated and vulcanized by dielectric heating or they may be preheated for forming and vulcanization in heated presses.

Another important application is the curing of rubber belting on a continuous basis. This has always been done on a batch basis with resultant under- or overcuring. Belts up to six feet in width and two inches in thickness are being processed.

Textiles and Paper. The addition of various resins to textiles in either thread or cloth form, or to paper, and their curing on a continuous-line basis by dielectric heating, offers a field of wide possibilities. Increased strength, moisture resistance, and life are only a few of the advantages.

Drying. The dehydration of hygroscopic materials to below five per cent has always been difficult. Dielectric heating is very effective and economical in the low moisture levels. For moisture contents of above 15 per cent conventional methods are usually more economical. Dielectric heating is used effectively in the dehydrating of ceramics, drug powders and tablets, tobacco, sand cores, and other materials.

Furniture Cementing. In the past, furniture makers almost unanimously have used animal glues. Experience with dielectric heating in the airplane and boat industries leads to the hopeful prediction that any joint normally used in furniture fabrication can be cured by dielectric heating, thus leading to anticipation of permanent and durable furniture after the war. An interesting development is that of "edge gluing" in which the resin joint is perpendicular to the dielectric plates. In this method the adhesive only is heated and cured in a fraction of the time required to heat the wood and joint.

Spot Fastening and Seaming. Dielectric guns for spot fastening of wood or fabric and electronic sewing machines for seaming or joining fabrics are in successful use.

Cooking of Foods. Considerable interest centers about the possibility of cooking foods in a relatively short time because of the potential adaptation to production lines. Research is being conducted in many places, but results to date are varied. Tests are being made on bakery products, ground meat, peas, beans, and nuts, and on the precooking of hams. Successful and economic application in this field is yet to be determined.

ECONOMICS OF DIELECTRIC HEATING

Although a superficial study of a contemplated application of dielectric heating may reveal a relatively high cost of equipment and a cost of energy absorbed by the product somewhat higher than competitive convential forms of heating, typical installations of dielectric heating invariably are highly economical for one or several of the following reasons:

(*a*). It produces results impossible by any other method of heating.

(*b*). Increased production usually is obtained.

(*c*). Output from present machines is increased, sometimes several fold.

(*d*). It occupies small space.

(*e*). It can be built into production lines.

(*f*). It assures optimum results.

(*g*). Output and quality can be predicted and controlled.

(*h*). Operation can be timed and sequenced by semiautomatic means so that only unskilled labor is necessary.

The over-all appraisal of investment, operating, labor, and energy costs, production, and quality usually prove overwhelmingly favorable to dielectric heating.

SUMMARY OF PRESENT STATE OF THE ART

Dielectric heating has been developed, tested, applied, and proved satisfactory in a wide variety of fields. Practically all of this development has taken place during the war period and it is natural that all applications are related to the war effort. The equipment, like other equipment requiring strategic materials and labor, is under all wartime controls. It is readily apparent that the full extent of its usefulness to industry has not been reached. As a working tool it has widened the horizon of possibilities by accomplishing uniform and controlled heating throughout the mass of low-thermal-conductivity materials—a condition which had never been successfully achieved before its advent. In certain other fields it is competitive with other forms of heating. Where economy dictates large quantities of low-cost heat energy, dielectric heating is not considered competitive.

Equipment development has reached a very high state of reliability. There are about ten manufacturers in the national field; five of them operate locally. Equipment in all sizes ranging from 1 to 75 kw in self-contained units and up to 300 kw in assemblies is now available. Adaptations and variations for any conceivable application are readily available. Cost of the dielectric units varies from $1,500 for the one-kilowatt unit to $200 per kilowatt for the 300-kw unit, without accessory equipment.

LABORATORIES CONDUCT RESEARCH

Extensive research is being conducted by equipment manufacturers and others. The standard procedure is to test the problem in the laboratory before making an installation. Research experts report that many problems which had been proved mathematically to be impracticable were nevertheless satisfactorily solved in the laboratory. In the laboratory of the company with which the author is associated, where several manufacturers co-operate in investigating problems submitted by industries, upwards of 90 projects were investigated during 1944, a majority of them with success.

Musings of an Engineer–Doctor

ARTHUR B. BERRESFORD

An engineer–doctor explains the differences in training and temperament between the engineer and the medical man and shows why these differences occur.

HAVING the good fortune to have degrees in both engineering and medicine, I am frequently asked such questions as, "Does your engineering help you in your medical work?" "Do you like medicine better than engineering?" "What about these doctors? Are they as scientific as they claim to be?" "Why aren't doctors more progressive, especially in such things as socialized medicine?" and so on ad infinitum.

I cannot begin to answer all these questions thoroughly, and I am not going to try. But I began thinking during a recent illness, when I was the patient for a change (which I found to be a rather difficult role to play), that it would amuse me to put down some of my thoughts on the subject of engineering versus doctoring. I must apologize in the beginning, however, which I am told is psychologically a very bad thing to do—first of all to you, because I must make this a highly personalized article and because it is not a scientific article such as you have every right to expect in a scientific publication, and second, to my profession, the medical profession, for perhaps exposing some of its little foibles that might better be left undisturbed.

THE DOCTOR–ENGINEER COMBINATION

I know of only two graduate engineers besides myself who have switched to medicine; one was a classmate of mine in engineering school. Doubtless there are others. And doubtless they have been kidded time and time again as I have about proposed rate schedules, such as:

Aerials strung	$10.00
Anesthesia	10.00
Belly ache	3.00
Bladder shot	7.50
Condenser shot	1.00
New tube	1.50
Tonsillectomy	50.00
Tubes tested	0.50
Wassermann test	2.00

If a patient chances to discover that I have been exposed to engineering, his first reaction is to stare blankly at me with his mouth gaping. Then he shakes himself, which seems to bring him back to consciousness, and finally he usually comes out with some facetious remark such as, "Call Doctor Berresford. He'll fix your lamp and your lamps," which he thinks is very funny. After that he returns to normal—that is, as normal as any patient ever gets. If the patient were normal, he would not be a patient!

The practice of medicine is just about as different from the practice of engineering as the Wassermann test is from tube testing. They are two different worlds conducted by groups of people who are as far removed from each other as the North and South Poles. But why should this be so? Aren't they all scientists? Yes and no.

Arthur B. Berresford, E.E., M.D., Ithaca, N. Y., is the son of the late AIEE Past President A. W. Berresford.

DOCTORS AND ENGINEERS ARE EMPIRICISTS

Let us take first the engineer, the man who is doing routine designing, not the inventer who has conceived of new realms for the application of engineering. How much of a scientist is he? He knows that $E=IR$ and that $F=MA$. Besides those two fundamentals, he has at hand to help him various handbooks, files, and pamphlets containing information about certain pieces of equipment, much of this information entirely empirical. From this, and perhaps the formula $ads=vdv$, plus a smattering of mathematics, he goes ahead and designs his equipment. Is he a scientist?

Now let's take the doctor—not the research man in the laboratory who is delving into new methods and working out new concepts of treatment—but *your* doctor, the man you call in when the wife is sick, or the specialist who prescribes your glasses. He has as his armamentarium a stethoscope and a sphygmomanometer, a thermometer and an ophthalmoscope. He knows that, if the sounds in your chest are not quite right or if your blood pressure or temperature deviates from the normal or the retina of your eye does not look as it should, it means that various and sundry things are wrong with you. He uses the scientific approach by first finding the cause of the trouble, but most of his diagnostic methods, while sometimes worked out initially on scientific grounds, are very like the engineer's formulas and handbook by the time they reach his hands. And treatment, in the last analysis, is largely empirical. He gives you some pills (he carries many which are quite entrancing in their variegated hues and shapes), and then he waits to see what will happen. For, if he is honest, he knows that the actions of the drugs and the reactions of the body to them are highly variable. Morphine usually kills pain and quiets a person. But it turns some patients into raving maniacs. Castor oil is one of our best laxatives; but in small quantities it is very constipating. Is he a scientist?

Neither your routine engineer nor your routine doctor is a scientist. Both apply their knowledge of scientific principles as far as they will go, but neither is an Ohm or an Osler. It is the Ohms and the Oslers, the Langmuirs and the Landsteiners that are the scientists in engineering and medicine. Not Mr. Smith or Doctor Brown. Between Mr. Smith and Doctor Brown there is a great difference. "Very good," you say. "But just what is this difference between Mr. Smith and Doctor Brown?"

To get this point across, I must again resort to personal references. I studied electrical engineering first but decided before I had finished that I wanted to study medicine. I finished the engineering just for pure cussedness, but what electives I had I took in premedical subjects, much to the disgust of the director of the school, the late P. M. Lincoln, who told me more than once that I was crazy; on more recent and mature thought, I am inclined to agree with him. In fact, I think all doctors are crazy, but I am digressing.

MEMORY AND REASON IN EDUCATION

In engineering I had been taught something called "the scientific approach." We found out for ourselves that E did equal IR and that it never failed to do so. Through other experiments and deductive work we built from this a large part of the theory and practice of electrical engineering. But when I started to study premedical subjects, which certainly were scientific, I found myself in a terrible jam. There was no $E=IR$ to cling to. In embryology we spent a whole term in the lecture room and laboratory studying the amazing and absorbing spectacle of a human being formed from the egg and sperm which, in uniting, set off the cycle that would result some day in, say, the editor of a scientific journal. It was a whole new field, completely wonderful, but lacking one thing. There was no $E=IR$ that could be applied to it. By process of reason you could not figure out how the embryo was going to form; it became necessary to memorize. I had never been taught to memorize, and it was very difficult for me. I needed my $E=IR$.

That is the big difference between the average engineer and the average doctor. To the engineer everything is built on reason, with a lot of reference, but with a very minimum of memory. The doctor on the other hand relies largely on his memory and also uses a lot of reference, but can get along with a relatively small amount of reasoning.

There is another fundamental difference between engineer and doctor which is second in importance only to that just mentioned. I expect that every engineer and every doctor that has ever graduated, with the exception of a few "big heads" who are not worthy of consideration, has felt not a little trepidation and doubt about his own ability to go on in his chosen field. The engineer usually goes to work for some manufacturing concern and finds that he still has a lot to learn but that if he is reasonably industrious his boss will help him along and show him the ropes. As time goes on, he finds that he has become an integral part of a system—a co-operative system designed to do some particular kind of work. He learns to rely on those about him for their share of the work and to co-operate with them.

The doctor does the same thing. He enters a hospital as an interne and finds that there is much he does not know, but the boss helps him along, providing he is reasonably industrious. He soon finds, like his engineer brother, that he has become part of a system, and he learns his place in it and how to co-operate with others. Some doctors remain in such positions, although of course on an advanced plane. They like the security of having consultation always available, of having others present to share responsibility, and of having regular time off and a steady income. Except for the primary difference, these men are essentially the same as the engineers. Both have become institutionalized.

DOCTORS EXCEPTIONALLY INDIVIDUALISTIC

But most doctors do not remain in an institution. After an interneship and residency lasting anywhere from one to six or seven years, a doctor leaves the hospital and "hangs out a shingle." It is a big step when a doctor starts out in practice for himself. No longer is the protection of the institution available. From now on what happens depends only on him. Many is the day I spent in my office wishing that a patient would come in and at the same time being scared to death that one would. It takes more time and experience than can be gained in a hospital to find oneself in private practice. And in order to find oneself in private practice one big important thing must be learned, and that is self-reliance. That takes time, but it comes to every doctor who sticks to the job, and most of them do stick to it, because they know they will starve if they don't. To make the change from institutionalization to private practice, self-reliance must be learned. Most engineers do not have to go through this process, or, if they do, it is a more gradual one.

So now we see the reason behind the second important trait of doctors. They become of necessity self-reliant. This leads quietly and unconsciously into an attitude of self-sufficiency. And so is formed the greatest and ruggedest group of rugged individualists in the country. Although the scientific background behind medicine is the same for all of them, no two doctors are anything alike. They all use different methods and different remedies in treating their cases, and each usually thinks every doctor is wrong who does not do things his way. Which all boils down then to the fact that each doctor is convinced that he is the only man who knows the best way to practice medicine.

What I have just said is not 100 per cent true. There are certain diseases for which specific remedies or procedures are available which every doctor would use, and the only differences between the treatment by two different doctors would be in the various trivia required to keep the patient more comfortable, humor him, and so on. But in those diseases like the common cold, whooping cough, and measles, where there is no specific treatment, there will be found as many treatments as there are doctors, and each doctor knows that his treatment is best.

Practically every doctor is a rugged individualist. Not so the engineers. Some do become rugged individualists, but the majority probably does not. And what are the characteristics of these individualists? In the first place, they are usually ultra-conservative in the sense that they do not want change. Secondly, they have difficulty in co-operating with members of the profession or outsiders, seeming at times to be quite irascible. Thirdly, they are the absolute monarchs of their own domains and often act as though they owned the world as well.

THE PROFESSIONAL MANNER

My analysis of the doctor's character would not be complete without considering another little doctor trait which is obvious to everybody except, apparently, the doctors. This usually goes by the name of "professional manner." It is an attitude of hearty aloofness, familiar to all laymen and just as false and characteristic of the species as the clergyman's superpiety or the undertaker's mournful face and somber clothes. There is, or rather was, a reason for the doctor's hearty aloofness. The need for it is vanishing now, because more and more diseases are being conquered by specific remedies, founded on science, which work, and less and less of the practice of medicine is the art or guesswork of medicine. The doctor of a generation ago did not want to be asked the question, "Why?", because, for most of the things he did, he did not know the answer, but people expected him to know the answer, and he was afraid to say "I don't know." He therefore had to hold himself aloof and adopt an all-knowing attitude to make patients do as he said without question. At the same time, he had to be a hail fellow well met, or he would not get patients. From these two conflicting emotions, you get the professional manner, the bedside manner, or whatever you choose to call it. The engineer does not have to struggle between these forces and so, in this respect, is a more normal individual than the doctor. But doctors now are learning not to be afraid to say "I don't know."

THE DOCTOR'S SADISTIC STREAK

Earlier I said that on more recent and mature thought I was inclined to agree with Engineer Lincoln that I was crazy. I am not a psychiatrist and am not prepared to go into a learned discussion of the sanity of the medico. But certainly any man (or woman) who undertakes to study medicine and treat diseased humans must perforce have an enlarged sadistic streak in him somewhere. Normal people do not like to come in contact with death. Normal people do not like to hack a dead body to pieces as must be done to learn anatomy. Of all the dirty, filthy, nasty jobs which must be done in this world, those of the doctor (and the nurse) are the dirtiest, filthiest, and nastiest. Perhaps if the doctor foresaw this he would choose another profession. But I doubt it. I foresaw it, and practically all medical students must.

I have tried to give you the differences in training and temperament between engineers and doctors and to show how and why these differences occur. Now that we have done that, let us see if we can answer some of the questions posed at the beginning of this article.

ENGINEERING TRAINING—AID AND HANDICAP

First, does my engineering knowledge help me in my medical work? Yes and no. Since I was not trained in memory, it was difficult for me to absorb such subjects as anatomy, which is practically all memory and a big wad of it too. On the other hand, my knowledge of physics in general and electrical engineering in particular has been very useful a few times. Most doctors are poor physicists. They have had elementary physics in college and none since. Occasionally they get into trouble because of a lack of appreciation of some fundamental physical principle. As an illustration, in medical school we once were instructed to read for anatomy a chapter in a well-known textbook entitled "The Mechanics of Muscle." The discussion was good, though lengthier than it needed to be (a characteristic of medical literature), showing the different types of levers and how they worked. The author carried his trigonometric discussion along very nicely until the next to last page when he made the unfortunate assumption that the sine of an angle plus its cosine was equal to unity, and his whole thesis came tumbling down with a terrific crash which left all his conclusions wrong. For the fun of it I looked back through old editions to find out how long the mistake had gone undetected. It was still present in an edition 20 years old. I did not go back beyond that. It is corrected now!

Are the doctors as scientific as they

claim to be? Some are and some are not, but most of them are not. The background of medicine is science, and I have complete faith that scientific medicine some day will rid the world of most of its illness. The medical practitioner applies the scientific facts which the laboratory has shown him, but where the laboratory has not solved the problem, the "art" of medicine comes into play. And a very great part of medicine remains an "art" today. By art of medicine we mean the hunches that a doctor gets and uses and the hundreds of little things he can do to keep the patient comfortable and as happy as possible. A happy patient has a much better chance of a cure than an unhappy one, and much depends on the doctor's ability to create and maintain this happiness.

Why are doctors not more progressive, especially in obtaining socialized medicine? There are innumerable reasons. First and foremost, a doctor is afraid of losing his work. He distrusts change because of his rugged individualism. He is mortally afraid of someone coming along—anyone, but in particular a politician—and telling him how to practice, because he knows he practices differently from every other doctor and believes it his right to do so. He is afraid of becoming ensnarled in bureaucracy and red tape which will make him spend hours each day at his desk filling out and sending in reports when he should be out seeing patients or enjoying his fireside. He believes that no layman knows his problems; and he is right, for his problems differ from everyone's else. You will not find a physician who is worthy of the name, and the vast majority are, who will not welcome any reform which will give better medicine to more persons. The majority of physicians are in favor of hospitalization and health insurance. But just bring the name of a state or the Federal Government into it and he will shy off every time.

MEDICINE AS A SOURCE OF PERSONAL CONTENTMENT

And for the $64 question, we have left the one which I am asked most frequently, "Do you like medicine better than engineering?" The answer is yes. But by that I do not mean that everybody should like medicine better than engineering. Both fields have a background which goes back to the ancient world—beyond the age of history. The engineers are less conscious of it than the medicos. The medicos like the ancient aspects of their profession, their Hippocratic oath which, though pretty badly outdated, is still taken by all doctors today. I like the history and background of medicine and like to feel myself at least a small part in a movement which must be destined some day to bring us greater rewards than we can now imagine. I got a kick out of building and operating a small broadcasting station for four years, but it is nothing like the kick I get out of seeing invalids transformed to health and knowing that I was instrumental in the transformation. I must confess, however, that I did not switch from engineering to medicine, because I was filled with charming pictures of helping sick humanity. I did it, because, while realizing my limitations, I liked to look upon myself as a scientist, and because I considered then, and consider today, the study of the human body to be the greatest of the sciences. I know that I shall never become a great scientist, but there is a vicarious pleasure in working in the field of the greatest science and applying the findings of the greatest scientists in that field to my everyday work. And who knows? It may just happen that I will be able to contribute a little bit myself some day.

Effect of Altitude on Electric Apparatus

L. M. ROBERTSON
MEMBER AIEE

This article summarizes the research work and investigations which have been conducted the last few years on the effect of altitude on rating, testing, and operation of electric apparatus. Existing Standards in this field and possible modifications of them are considered.

INCREASE OF ALTITUDE results in decrease of air density, heat dissipation by convection, dielectric strength of air, windage losses, ambient temperature and humidity, and this affects operation of some electric apparatus. Corona loss, lightning currents, commutation, and earth resistance also are affected. Much research work and investigation have been carried on, and this paper summarizes some information on this subject.[1-3]

IMPULSE VOLTAGE DATA

Many tests have been made to determine the effect of altitude on impulse and 60-cycle strength of electric apparatus. The author reports that operating experience, at high altitudes in Colorado, with equipment and lines indicates that the reduction of impulse strength must be taken into account, and greater spacing of bushings and longer length must be provided. Apparatus rated 15 kv and operating at 13 kv at 5,280 feet altitude has failed repeatedly, and 23-kv bushings, apparatus, and insulators have been found to be desirable. Group-operated air-break switches rated 115 kv and operating at 10,200 feet and 11,300 feet altitude flashed across the open switches on switching surges with an opening of 42 inches, but did not when this gap was increased to 49.5 inches. It has been found necessary to use 55-kv insulators on 44-kv wood-pole lines, and special-design lightning arresters are necessary for altitudes above 6,000 feet. Lack of contamination in the air at high altitudes has resulted in successful operation of transmission lines at 100 kv and 110 kv with seven suspension insulators in a string. The low humidity at high altitudes increases the dielectric strength of the air and probably accounts for the reduced depreciation of insulating oil and less frequent failure of bushings than at sea level.

Laboratory tests on the effect of altitude on impulse and 60-cycle strength of electric apparatus reported most recently[1] were made in a sealed Micarta cylinder enclosing the apparatus for test, and desired pressures were maintained in the cylinder. Measurements of pressure, humidity, and temperature were recorded. The apparatus tested included 15-kv and 69-kv switch and bus insulators; 69-kv bushings; six-unit ten-inch-diameter suspension insulator string; 15-kv dry-type insulator; 15-kv and 8.66-kv air-insulated transformers; six feet of 66-kv wood crossarm; 6-, 12-, and 24-inch rod gaps; and one-half-inch transformer oil gap. The applied full-wave impulse test voltages were $1^1/_2 \times 40$ microseconds. Figures 9, 10, and 11 of reference 1 show

This article is based on three conference papers presented by L. M. Robertson, P. L. Bellaschi, and V. M. Montsinger, at the AIEE Pacific Coast technical meeting, Salt Lake City, Utah, September 3, 1943.

L. M. Robertson is transmission and station engineer, Public Service Company of Colorado, Denver, Colo.

Table I. Relative Dielectric Strength for Altitudes Above 3,300 Feet (1,000 Meters) at Any Given Temperature*

Altitude	Altitude Correction Factor for Dielectric Strength
3,300 feet (1,000 meters)	1.00
4,000 feet (1,200 meters)	0.98
5,000 feet (1,500 meters)	0.95
6,000 feet (1,800 meters)	0.92
7,000 feet (2,100 meters)	0.89
8,000 feet (2,400 meters)	0.86
9,000 feet (2,700 meters)	0.83
10,000 feet (3,000 meters)	0.80
12,000 feet (3,600 meters)	0.75
14,000 feet (4,200 meters)	0.70
16,000 feet (4,800 meters)	0.65
18,000 feet (5,400 meters)	0.61
20,000 feet (6,000 meters)	0.56

The dielectric strength of equipment which depends upon air for its insulation varies with altitude.

* From AIEE Standard 1*B*.

the results of these impulse tests and indicate that, in the case of apparatus, the air strength is essentially proportional to the relative air density; but the time to flashover in the lower air densities is longer, being seven microseconds at 0.97 relative air density and 27 microseconds at 0.47 relative air density. Wood was found to be quite variable on impulse test but showed a reduction of impulse strength with reduction of relative air density and an increase of time to breakdown. Table II of reference 1 shows the atmospheric conditions at various altitudes.

SIXTY-CYCLE DATA AND CORONA

The laboratory tests seem to indicate that the 60-cycle strength of apparatus can be taken as practically proportional to relative air density (Figure 14 of reference 1). This has been borne out by actual operating experience. AIEE Standard 1*B* gives the relative dielectric strength of equipment which depends upon air for its insulation for altitudes above 3,300 feet (1,000 meters) as shown in Table I.[3]

Table II. Proposed Corrections of Observed Temperature Rise for Variation in Altitude*

(*a*). When tests are made at an altitude not exceeding 3,300 feet (1,000 meters) above sea level, no altitude correction shall be applied to the temperature rise.

(*b*). For standard apparatus tested at an altitude in excess of 3,300 feet (1,000 meters) above sea level, it will be assumed that their temperature rise at any altitude 3,300 feet (1,000 meters) or less will be the temperature rise observed at the higher altitude reduced by the following percentages for each 330 feet (100 meters) that the altitude exceeds 3,300 feet (1,000 meters):

Oil-immersed self-cooled apparatus	0.4 per cent
Oil-immersed water-cooled apparatus	0.0 per cent
Oil-immersed self-cooled or forced-air-cooled apparatus at forced-air-cooled rating	0.6 per cent
Oil-immersed forced-oil-cooled apparatus with oil-to-air cooler	0.6 per cent
Oil-immersed forced-oil-cooled apparatus with oil-to-water cooler	0.0 per cent
Dry-type self-cooled apparatus	0.5 per cent
Dry-type forced-air-cooled	1.0 per cent

* Based on American Standard C57.2, section 10.104.

Table III. Proposed Guides for Loading When Standard Apparatus Is to Be Operated at High Altitude

To permit the selection of standard apparatus for application at altitudes in excess of 3,300 feet (1,000 meters) above sea level the reduction in kva due to change in air density with altitude shall be as given below for each 330 feet (100 meters) that the altitude at point of operation is in excess of 3,300 feet (1,000 meters) above sea level, and not exceed standard limits of temperature rise.

Oil-immersed self-cooled apparatus	0.4 per cent
Oil-immersed water-cooled apparatus	0.0 per cent
Oil-immersed self-cooled or forced-air-cooled apparatus at forced-air-cooled rating	0.5 per cent
Oil-immersed forced-oil-cooled apparatus with oil-to-air cooler	0.5 per cent
Oil-immersed forced-oil-cooled apparatus with oil-to-water cooler	0.0 per cent
Dry-type self-cooled apparatus	0.3 per cent
Dry-type forced-air-cooled	0.5 per cent

Corona measurements have been made in Colorado on a 100-kv line at an average altitude of 6,000 feet and another at 10,000 feet, the length being 21.5 miles and 155 miles, respectively. Figure 1 shows the results of the tests on the shorter line at 6,000 feet altitude and indicates that the measured loss is less than the value calculated by Peek's or Peterson's formulas. Calculations of corona loss on the longer line at the higher altitude by Peek's formula gave 955 kw instead of the actual loss of 237 kw. When the altitude of the line was decreased in the calculations by 3,500 feet, the results gave the same value of loss as that actually measured. Corona has been observed in generators and cables but under conditions which might have produced corona at lower altitudes.

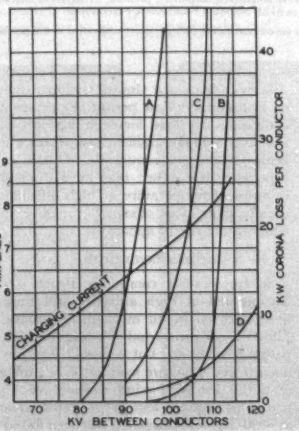

Figure 1. Corona-loss curves for the Boulder Canon (Colorado)–Denver 100-kv transmission line

Corona loss is per 1/0 hemp-center copper conductor for 21.51 miles of flat construction with spacing of ten feet four inches between conductors

A—Calculated from Peek's formula

B—Tested with wet-bulb temperature of 7.7 degrees centigrade and dry-bulb of 9.5 degrees centigrade

C—Calculated from Peterson's formula for 1/0 hemp-center copper conductor at 9.5 degrees centigrade

D—Calculated from Peterson's formula for 3/0 seven-strand copper conductor at 18.5 degrees centigrade

TEMPERATURE RISE

Stationary Induction Apparatus. Equipment which depends on air for its cooling medium will indicate an increase of temperature rise with increase of altitude. Heating of modern oil-insulated self-cooled power transformers operating at various altitudes up to 11,300 feet has been studied, and the observed temperature rise has been somewhat higher than calculated values would indicate, although in a few cases it was actually less. However, the manufacturer's designs appear to be satisfactory.

V. M. Montsinger points out that the derivation of the correct altitude correction factors for self-cooled transformers is complicated, because oil-insulated transformers are cooled by convection, which is affected by altitude, and by radiation, which is not affected by altitude. The division depends on the contour of the tank with the correction factor expressed in terms of winding temperature rise, and the correction starting at 1,000 meters (3,300 feet), not sea level. The effect of altitude on temperature rise can vary as much as 2.35:1, depending on the ratio of the developed area (effective for convection) to the sum of the developed area and the outside envelope area (effective for radiation) of the cooling surface. Representative ratios are 0.5 for small distribution transformers, 0.9 for large power transformers, and 1.0 for dry-type self-cooled transformers where air is flowing up the windings. Therefore, there is no one correction factor which can be applied accurately to all self-cooled transformers.

Table IV*

Altitude in Feet	Altitude in Meters	Maximum Temperature of the Cooling Air in Degrees Centigrade
0– 3,300	0–1,000	40
3,300– 6,600	1,000–2,000	35
6,600– 9,900	2,000–3,000	30
9,900–13,200	3,000–4,000	25

It is recognized as good practice to use machines of standard temperature rise at altitudes greater than 3,300 feet (1,000 meters), provided the temperature of the cooling air is not likely to exceed the foregoing values for the respective altitudes.

* From American Standard C50.

Table II shows the proposed corrections

Table V. Altitude as a Factor in Apparatus Standards

Standard	Apparatus	Usual Service Conditions	Correction Factors (Per Cent Per 100 Meters Altitude Exceeds 1,000 Meters)		Other Correction Factors Specified*
			Voltage Rating	Temperature Rise	
AIEE 4 —1943	Measurement of test voltage in dielectric tests				Relative air density
AIEE 11 —1943	Rotating electric machinery on railway locomotives	Altitude not exceeding 1,000 meters	1	0.4	
AIEE 19 —1943	Oil circuit breakers**			0.4	Relative air density
AIEE 21 —1942	Apparatus bushings				
AIEE 22 —1942	Air switches and bus supports**		1	0.4	
AIEE 24 —1940	Protector tubes				
AIEE 25 —1941	Fuses above 600 volts		1	0.4	
AIEE 27 —1942	Switchgear assemblies**		1	0.4	
AIEE 28 —1943	Lightning arresters				
AIEE 31 —1941	Capacitance potential devices and coupling capacitors				
AIEE 32 —1942	Neutral-grounding devices	This standard follows transformer standard			
AIEE 36 —1928	Storage batteries	No limit			
AIEE 41A—1942	Insulator tests				Relative air density
ASA C57.1, 2, 3—1942	Transformers, regulators, and reactors	Altitude not exceeding 1,000 meters (No limit for water-cooled)	Water-cooled: 0 Oil-immersed, self-cooled: 0.4 Dry-type: 0.5 Oil-immersed, forced-air: 0.6 Air-blast: 1.0		Guide for operation permits overloading for lower ambient temperature
ASA C50—1936	Rotating electric machinery	Altitude not exceeding 1,000 meters	1.0		For low ambient temperature std. temp. machine applicable to higher altitude decreased in windage loss, proportional to relative air density
ASA C19—1943	Industrial-control apparatus	Altitude not exceeding 6,000 feet	Above 6,000 feet and not exceeding 15,000 feet continuous-duty resistors autotransformers, control-circuit transformers derated to 75 per cent. Other provisions stated		

** Dielectric tests of air-insulated apparatus are referred to 760 millimeters barometric pressure, 25 degrees centigrade temperature, 15.45 millimeters mercury absolute humidity Voltage measurement and correction are made according to AIEE Standard 4 and AIEE paper 40-38.

* Present revisions of these Standards specify a correction for current rating (0.2 per cent) equivalent to 0.4 per cent based on temperature rise.

for observed temperature rise for variation in altitude, and Table III the proposed guides for loading when standard apparatus is to be operated at high altitudes. These tables have been prepared by Mr. Bellaschi and submitted to the transformer subcommittee and are being incorporated in American Standards C57.2 and C57.3.

Rotating Machines. The present American Standard C50 for rotating machines gives a correction factor for temperature rise of 1.0 per cent per 100 meters that the altitude exceeds 1,000 meters. The guide for service conditions[3] gives the supplementary information for this Standard shown in Table IV.

Table V has been prepared by Mr. Bellaschi to show how altitude is considered as a factor in the present apparatus Standards.

AMBIENT TEMPERATURES

Mr. Montsinger indicates in his paper that the United States Weather Bureau observed that the average decrease in temperature with elevation is about one degree Fahrenheit for 330 feet (5.5 degrees centigrade per 1,000 meters). Temperatures have been recorded in Colorado on the earth's surface from 4,000 feet to 13,500 feet, and the decrease found to be 3.5 degrees Fahrenheit per 1,000 feet increase in altitude. This has been taken into account in loading of equipment in service where it applies, and the American Standard Guides for Operation of Transformers now permit one-per-cent continuous overload for each degree that the daily average ambient temperature is below 30 degrees centigrade. Operating experience has shown that the reduction in ambient temperature at high altitudes usually more than offsets the increase in temperature rise of apparatus.

STORM CONDITIONS

Severe weather conditions always are encountered at high altitudes and must be considered in all mechanical designs. Efforts to measure wind velocities on high passes have failed, but a design for conductors and structure loading of $1^1/_4$ inch of radial ice with wind pressure of 15 pound per square foot of projected area at −50 degrees Fahrenheit has been found by trial to be satisfactory for service in high passes.

Measurements of lightning-stroke currents[2] up to altitudes of 13,600 feet indicate that the current may be less at high altitudes, but the high ground resistance and reduced insulating value of the air encountered requires special designs for lightning protection. Earth leakage or corona current continuing over a considerable length of time may be the cause of arrester failure and disturbances on lower-voltage circuits.[3]

CONCLUSIONS

Tests and operating experience show that the impulse voltage strength of parts in air is essentially proportional to relative air density.

Operating experience has indicated a need for overinsulation on most applications at high altitudes.

Measured corona losses on 100-kv lines at 6,000 and 10,000 feet altitude have been less than the calculated values.

The increase of temperature rise with increase of altitude of certain apparatus has been confirmed by tests and experience.

Operating experience has shown that the reduction in ambient temperatures with increase of altitude usually more than offsets the increase in temperature rise of apparatus.

Severe weather conditions at high altitudes require special mechanical designs for structures and line conductors.

Lightning-stroke-current values at high altitudes may be less than at sea level, but special designs are required for lightning protection because of high ground resistance and reduced insulating value of air.

REFERENCES

1. Effect of Altitude on Impulse and 60-Cycle Strength of Electrical Apparatus, P. L. Bellaschi, Paul Evans Jr. AIEE *Transactions*, volume 63, 1944, May section, pages 236–41.

2. Lightning Investigation at High Altitude in Colorado. L. M. Robertson, W. W. Lewis, C. M. Foust. AIEE *Transactions*, volume 61, 1942, April section, pages 201–8.

3. Report on Guiding Principles for the Specification of Service Conditions in Electrical Standards, AIEE Standard *1B*, May 1944.

Lighting and Safety

H. L. LOGAN
FELLOW AIEE

Proper illumination, a potent factor in industrial and traffic safety, is considered from all angles, including man's physiological and psychological reactions to lighting. The author stresses the present need for technical skill and technical knowledge—in short, for illuminating engineers of a high order.

THE "Proposed American Recommended Practise for Compiling Industrial Accident Causes" (see Table I), lists nine causes, three of which are personal and six impersonal, or environmental. The National Safety Council assigns 70 per cent of all accidents to the one third of the causes listed as "personal" and only 30 per cent to the two thirds of the causes that lie within the influence of the worker's environment. One of the six environmental causes, "improper illumination" (more inclusively, uncertain sight), is judged responsible for only four tenths of one per cent of industrial accidents. The insignificant percentage of accidents *attributed* to uncertain sight as influenced by lighting conditions is a measure of the educational job that faces lighting engineers in industry.

Light is not recognized as a major cause because it is the cause behind the cause.

H. L. Logan is managing engineer, controlens division, Holophane Company, Inc., New York, N. Y.

The truth of this statement is more readily recognized when the fundamental physiological function of the eyes is understood. The eyes are mechanisms for "survival." They are the major safety devices of the human animal. Their prime physiological function is to control the orientation and posturing of the body in its environment in such a way as to protect the body from hazards, or to gain benefits for the body, for example, in its search for food; that is, to ensure survival.

This is accomplished by a tie-in between the nerve networks of the eyes and the muscles so that reflex (automatic) actions may be initiated by the changing patterns of light in the eyes. This tie-in is exclusive in primitive forms of moving life so that their light-responsive organs initiate reflex actions of the muscular system only and do not convey images to a brain. In man this tie-in persists as an important mechanism for survival.

FUNCTION OF LINE OF SIGHT

The ability of human beings to "see" is but one of the processes set into action by the eyes. Man is prone to recognize it as the only one, because it is the function that has enabled him to develop a civilization and to engage in cultural activities, but his individual safety and well-being remain closely dependent upon the light pattern that reaches his eyes from the entire field

Westinghouse Photo

Figure 1A. Rod lying on the floor can hardly be noticed in the dim lighting and constitutes an accident hazard

Westinghouse Photo

Figure 1B. Good general lighting throughout the area reveals this rod clearly so that no one would be likely to step on it and fall

Westinghouse Photo

Figure 2A (left). Pedestrian is barely visible. Reflections from the road are largely skyward, and road surface appears black to motorist

Figure 2B (right). "Silhouette of safety." Reflection in road is in motorist's direction and road surface appears bright to driver

Westinghouse Photo

Table I. Accident Causes

From National Safety Council Data

	Relative Importance	Percentage	Accident Causes	Suggestions for Corrective Action
The worker	1	30	Lack of knowledge or skill	Job analysis Job training
	2	20	Unsafe procedure Unsafe housekeeping Bodily defects	Formulation of safe procedure. Supervision discipline. Physical examinations
	3	19.1	Improper attitude	Supervision discipline. Personnel work to remove worry
The worker's environment	4	13.1	Agencies defective through use or design	Inspection. Proper maintenance
	5	9.5	Unsafe dress	Specify proper dress and equipment
	6	5.6	Improper guards	Inspection design with guards
	7	1.8	Unsafe housekeeping facilities	Supervision discipline. Job analysis; training
	8	0.5	Improper ventilation	Improve ventilation
	9	0.4	Improper illumination	Improve illumination

of view, rather than upon the stimulus received from the objects he can see clearly along his line of sight. If this light pattern, or a person's ability to react to it efficiently, is defective, that person is potentially unsafe, or accident-prone, in that environment.

PHYSIOLOGICALLY SAFE LIGHTING

Emphasis on the use of the eyes as visual organs only has led to the use of light in industry for seeing only, to the involuntary neglect of the need for physiologically safe-lighting conditions; and it is this same pre-occupation with eyes as "seeing tools" that has delayed a full recognition of the major role that proper lighting can play in safeguarding all human activities.

Until the present time safety levels of lighting have been considered to be the least light necessary for seeing in the judgment of an observer who made a leisurely survey of a particular site. However, such a test does not take cognizance of the workman who trips over something. The foreman puts the accident down to a personal cause—carelessness—not realizing that, although there was enough light for the workman to have seen the bar (Fig. 1A) if he had studied the floor, there was not sufficient light to attract his attention to the bar in time to prevent his stumbling over it at the normal speed at which the workman should and did move.

The old proverb, "Look before you leap," is sound advice, but it is no help in the dark, and a workman is always moving into physiological darkness when he moves from the relatively high level of brightness of his work into a surrounding level to which his eyes are not adapted. It must be remembered that it takes 60 times longer to adapt eyes to a lower level of brightness than to a corresponding higher level.

There is not time in modern high-speed industry to make these downward adaptations; but, when they are not made, and an accident happens, the workman is charged with carelessness instead of the management's being charged with failure to make the proper environmental adjustment to elementary physiological facts.

A great mass of reports dealing with "flying particles," "falling objects," "striking stationary objects," "falls," and "contact with moving machinery" has piled up and hidden the true cause of many accidents—uncertain sight.

Uncertain sight causes accidents:

1. When there is not sufficient light to reveal the hazard clearly.
2. When the level of illumination, although good for leisurely observation, is not enough to force the observer's attention to the hazard under normal conditions of speed and preoccupation of the observer.
3. When the hazard is camouflaged by brightness, such as glare or by color which might give it the same brightness as the background and so conceal it, or by shadow which might hide the hazard.
4. When the eyes are defective. Defective eyes benefit from proper lighting, but the best light will not compensate for inherent eye defects. Such eyes should be corrected to normal.

What proof is there that accidents caused by improper lighting are a major group? First, there is the general proof of the paramount part played by sight as the major sense. Most authorities agree that more than 85 per cent of our activities are controlled by sight and the remaining 15 per cent by the other four senses. Therefore, if accident causes were classified in relation to the senses involved, 85 per cent of accidents would be ascribed in whole or in part to uncertain sight.

A statistical study shows that 22 per cent of industrial accidents happen to the fingers (Figure 3). The implication is strong that, in the absence of sufficient illumination, many workers are forced to rely unduly on their sense of touch.

Accidents in homes are twice as great as accidents in industry, added to accidents in traffic, plus war casualties. Reason—homes are notoriously underlighted. Of the approximate 5,000,000 which occur in homes annually 21 per cent of these occur on the porch and outside steps—the two most poorly lighted locations throughout the major portion of each 24 hours most of the year. Another 12 per cent occur in the halls, which also usually are underlighted. The kitchen claims 18 per cent. This is often the best-lighted part of the home, but when the kind of operations that are performed in the kitchen are compared with their counterparts in industry it will be found that the kitchen is poorly lighted for the work done there. Average kitchen illumination is five foot-candles for work that industry lights to 20 foot-candles, and more recently to 50 foot-candles. In short, at least 50 per cent of home accidents occur in locations that lighting engineers know to be invariably underlighted.

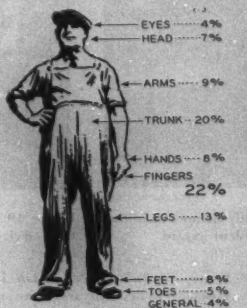

Figure 3 (above). Where accidents strike

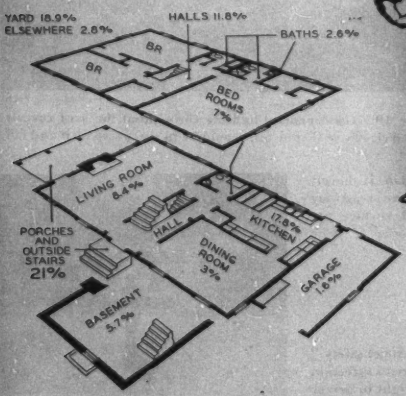

Figure 4. Where accidents occur in the home

Architectural Record, May 1941

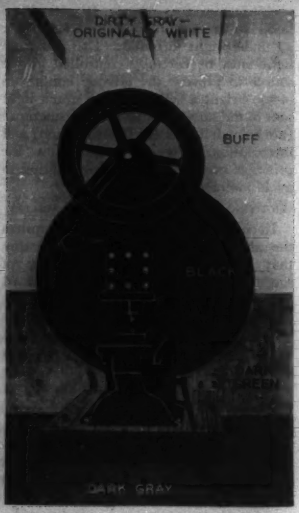

Figure 5. Drab-finished machine in a drab-finished interior

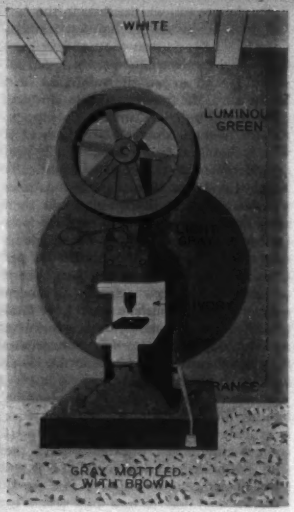

Figure 6. Same machine after scientific repainting

The most striking proof lies in traffic-accident experience. For example, a traffic survey in Trenton, N. J., early in 1937 uncovered a relatively high percentage of night accidents, with a considerably higher incidence at 33 intersections. At these intersections night accidents were 59 per cent of the total, while in the city as a whole only 42 per cent of all accidents occurred at night. These intersections were then scientifically lighted. Injuries decreased 40 per cent and fatalities 50 per cent at night. The economic loss owing to the night-traffic accidents at the 33 locations before improvement was $89,900. After improvement the loss was $52,700. The improvement cost $3,292 per year, proving once again that it costs less to prevent accidents than to pay for them.

RELATIONSHIP BETWEEN LIGHT AND ACCIDENTS

The relationship between light and accidents is clearly indicated in the traffic figures of the borough of Manhattan, New York. There were 118 daytime fatal crashes in 1941 and 151 fatal crashes at night, despite the smaller traffic load at night. In 1942 under dim-out conditions, although daytime fatal crashes dropped to 86 owing to fewer cars on the streets, fatal crashes at night jumped to 254.

During the dim-out period of the war, night-traffic accidents in six of the principal communities of Connecticut increased 56.7 per cent over the rate in the same communities when normal street lighting was used.

Detroit had 96 fatal nighttime crashes on 100 miles of its streets selected for special study during the two years of 1935–36. Street lighting was scientifically improved on these streets in 1937. The total fatal crashes by night for the succeeding three years numbered 34. Examples of this kind can be cited indefinitely.

The objection has been raised that traffic-accident experience has no bearing on industrial-accident experience. The answer is that the eyes are obeying the same light stimulus, whether in night traffic, or in the factory, and are operating under the same physical and physiological laws. It is true that there are fewer complicating factors in analyzing traffic accidents so that the influence of lighting is more readily revealed. However, the underlying biological facts leave no room for doubting the fact that faulty illumination is the crux of both the industrial- and traffic-safety problem.

Moreover, since the writer first published a tentative curve[1] relating the accident rate to the adaptation brightness of the field of view, a number of industrial cases has been recorded in the February 1944 *Illuminating Engineering*, which show specific reductions in accident rates in 14 industries as a result of the application of scientific lighting principles.

E. E. Dorting of the Board of Transportation of City of New York showed in the September 1943 *Illuminating Engineering* the results of five years' researches into the effect of lighting conditions on the accident rate on stairways and at transfer points (getting on and off cars), in New York subways. He found a drop of 59 per cent in stairway accidents and 52 per cent in transfer-point accidents as a result of suitably raising the illumination at these places. His results check the curve referred to, because his before- and after-brightnesses, applied to the curve, give accident-rate decreases similar to those found in practice.

As the rate of accidents caused by insufficient lighting depends upon the mean brightness of the field of view it can be affected by the reflection factors of the field of view. For instance, a black interior with 600 foot-candles of illumination would have the same light-accident rate (other things being equal), as a white interior with only eight foot-candles. The eye works with the light it receives, not with the light sent out by the lighting fixtures. This is the underlying reason for the increasing popularity of the scientific painting of machines and industrial interiors. The principles are simple and are

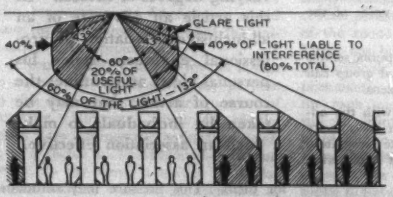

Figure 7A (left). Shows high light loss from interference when diffusing distribution in high bays is used

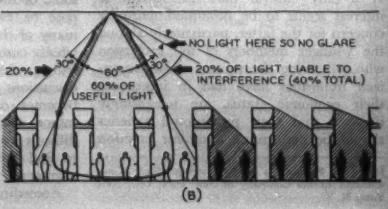

Figure 7B (right). Shows high gain in useful light when intensive distribution in high bays is used

illustrated in Figures 5–6. It should be noted that the foot lever is painted a strong color so that the workman can easily see it out of the corner of his eye.

The lower the level of illumination the more important is this matter of lighter scientific finishes. If an illumination of 15 foot-candles were being used the portion of the accident rate dependent upon uncertain seeing would tend to be 150 per cent higher with 10 per cent reflection factor than with 20 per cent. That is, accidents caused by improper illumination would tend to be 10 per cent of all accidents with the higher reflection factor and 25 per cent with the lower, and so this matter of the proper application of paint and other surface finishes to the whole field of the view of the worker is highly important in accident control.

Another matter of great importance is the relation of design levels of illumination to actual in-service levels. Experience shows that in-service levels are more likely to run 40 per cent of the design levels rather than 70 or 80 per cent (figures customarily used by industry and lighting engineers in computing lighting levels).

The failure to look the facts in the face and realistically design lighting installations has a bearing on the accident rate. Suppose an industrialist wants a safe installation and so sets the minimum field brightness at the required six foot-lamberts (for average industrial interiors); suppose also the average absorption of the field of view is the usual 80 per cent. If a 25-per-cent depreciation factor is optimistically assumed a design level of 40 foot-candles will be adopted. Experience will then show the brightness level to be three foot-lamberts instead of six and the accidents caused by improper illumination 50 per cent higher than they would have been if the six foot-lamberts actually had been realized. Such a mistake could have fatal results for one or more of the workmen and would be sure to cost the industrialist far more than he would save in the lower lighting cost.

Another point to watch in planning lighting for safety is to see that the work is at least as bright as the surround. If the general interior is brighter than the work, visibility goes down, and, if it is less than 40 per cent as bright as the work, visibility also goes down. It goes down faster for an overbright surround than for an underbright surround. Then, too, the light must be carefully controlled at the source to prevent the adverse conditions of too bright a surround (too much light sent to the surround), too dark a surround (not enough light sent to the surround) and interception. Figure 7 illustrates the principle involved in designing lighting to avoid interception losses.

LIGHTING REQUIRES ENGINEERING ABILITY

In conclusion lighting for safety requires the abandonment of the archaic notion that lighting design consists simply of spotting outlets and putting some standard light source and accessory on them. There is no room for rules of thumb or salesmen's recipes when human life may depend upon the correct answer. Lighting for safety in industry, just as in traffic, requires engineering ability and engineering knowledge of a high order—in short, it needs the services of qualified illuminating engineers.

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Organization of the Engineering Profession

JAMES F. FAIRMAN
FELLOW AIEE

The problem of organizing engineers for enhancement of the profession has had several proposed solutions, some of which have been tried with varying degrees of success. In this article an advocate of an all-inclusive association of professional engineers states his personal views and outlines the course of action that may be taken by individuals to make such an association effective.

DURING the last few years there has been a revival of interest in the problem of better organization of the engineering profession. There seems to be agreement that there is room for improvement and in particular that the outstanding need is for some agency that could and would be recognized as the voice of the profession.

1. In the field of disinterested public service which an organized professional group can and should render as good citizens.

2. In matters having to do with the advancement of the profession in its capacity for service and with appropriate recognition by the public of the value of engineering services.

It is only natural that the revival of interest seems to be prompted more by concern for the latter, particularly among the younger members of the profession who, observing the success which organized minorities have had in improving their economic status, are increasingly insistent that their professional societies should be performing a similar function for them. This pressure may stimulate some of the engineering societies to propose or even to adopt methods which many of their members will feel are not wholly compatible with the purposes of a truly professional organization. As these discussions proceed the basic problem becomes confused with a great many minor, if not extraneous, issues, and it is difficult for the members of the profession to find their way through the maze of argument.

Accordingly, it may be helpful to consider how we would organize the engineering profession to do the various things which we believe should be done if we could start fresh, free of any commitments, investments, concern for individual jobs or sense of obligation to the founding fathers, and particularly, without any prejudices or sentiment, but retaining our background of experience with the types of organization we have tried. If we can find a generally satisfactory solution to this problem perhaps we shall find it not nearly so difficult as we now think, within a reasonable time to approximate the ideal organization to accomplish our ends.

COMPROMISES NECESSARY

Such an approach is essential if we are to make the desired progress. We must put aside for the moment the particular associations of which we have been members these many years and to which we individually owe certain obligations and allegiance. We must forget all the background of division and subdivision of the earlier societies and the lingering suspicions and prejudices left in their train. We must be willing to make the sacrifices necessary to realize our objective. When

James F. Fairman is assistant vice-president, Consolidated Edison Company of New York, Inc., New York, N. Y.

we know what we want to do and have decided upon the best way to organize ourselves to attain our ends, then we may find it expedient or desirable to make certain adjustments or compromises the better to enable us to advance our program. But there is no need for us to start out devising compromises. Until we have mapped out our course, how can we determine whether or what compromise is necessary? Rather, let us be as bold in our attack on this problem as we are in our attack on a technical problem.

OBJECTIVE APPROACH DIFFICULT

Admittedly, a purely objective approach is difficult, especially to those most directly concerned, when we are dealing with a problem involving human relations. I am well aware that, in view of my activities in another organization, I shall be suspected of a certain degree of bias and perhaps even of a pernicious form of fifth-column activity. I am willing to take that chance in the hope of stirring up constructive thought and discussion among the members of the Institute who presumably will make an approach at least as objective as I am endeavoring to do.

The solution suggested here is neither new nor original. AIEE President Powel broadly suggested it in his article.[1] His forthright statements encouraged me to prepare this article describing in greater detail a solution whose only novelty lies in its appearance in these columns.

Inasmuch as there appears to be widespread agreement that the engineering profession needs "some association of engineers whose purpose is to represent all branches of the profession in civic and state affairs and which also is capable of watching over the welfare of its individual members in broad issues,"[1] "a central agency which can represent the entire engineering profession in matters of public concern,"[2] "some organization . . . similar in character to the American Medical Association and the American Bar Association to work toward the dual objectives of intraprofessional relations among engineers and a combined professional approach to public problems,"[3] there is no point in laboring the major premise. Accepting this premise and bearing in mind the suggestion that we start with a clean slate, it would seem obvious that there should be one basic organization of engineers devoted to the objectives of all engineers as professional men and as citizens. It would seem obvious too that this organization should be built along the most democratic lines and that every individual member should have as direct a voice as possible in its affairs. To encourage a maximum of participation by the individual member, the basic unit of organization should be the local chapter, confined to the smallest practicable geographic or political area. Probably the norm for this unit would be the county. For greatest effectiveness in dealing with civic and professional problems extending beyond the community, these local chapters should combine to form a state society, and the state societies in turn should unite in a national organization. Concurrent membership of the individual in each unit—the county or local chapter, the state society, and the national association—should be required and the scheme of operation should be such that the individual member is made continually conscious of his interest in and obligation to each of these three spheres of activity.

Perhaps there will be agreement up to this point although there may be some mental reservations about attaining such an ideal situation. Accordingly, before proceeding to describe this basic organization and its functions further in detail, it seems desirable to remind the reader of the opening admonition not to let the past impede our planning for the future.

ONE GRADE OF MEMBERSHIP

There should be just one grade and kind of membership—members, called by any name you please. Bear in mind that this is to be an organization of and for all engineers, and one of the best ways to defeat its purpose is to start making distinctions of any kind on any basis whatsoever, except the obviously necessary distinction between engineers and nonengineers.

This raises the question as to who or what is an engineer. Seemingly we have lacked the courage to face this question. There is one very simple answer which, like most simple things, is all the harder to grasp but which, if generally accepted, would go a long way toward the solution of some of our most annoying problems. It is similar to the answer long since accepted in the professions of law and medicine. I submit that an engineer should be any person legally recognized by the state as being qualified to practice the profession of engineering. If we would only accept that as our definition, together with its consequences, I believe we would have taken a major step toward the unification of the profession.

If you are still with me, let me hasten to assure you that it is not my purpose in this article to argue the question of licensing. However, when 46 of the states have engineering registration laws, it is a factor to be reckoned with and hence, in my view, a matter of fundamental concern to us as engineers and as citizens. Accordingly, some consideration of it in any discussion of the ideal organization of the profession is necessary. Ideally, should not the profession police itself as a self-governing, democratic body? If so, then licensing may be a useful means to that end by putting the authority of the state behind the determinations of an organized professional group, whose members, in the final analysis, should determine who should or should not be licensed, or to put it another way, who is and who is not an engineer. I think we shall have to admit that, as a professional group, we have not handled this matter as wisely as we might have done. So here is at least one specific task for our ideal common engineering society, and at least one reason for its organization along political and geographic lines.

Of course there are many other things which such a basic organization would do, and there probably will be honest differences of opinion as to which of these things are more important. Without attempting to make a complete list or to indicate their relative importance to the profession or to the public but simply as illustrative of the scope of such an engineering society as is here proposed, the following items, I believe, would be generally agreed upon as entitled to consideration.

A DEMOCRATIC ORGANIZATION

Continuing with the thought of professional self-government, it seems to me that our basic engineering society would naturally be concerned with a program similar to but going beyond that sponsored by Engineers' Council for Professional Development.[4,5] If the profession is to govern itself in a democratic fashion and with an eye to the public interest it would seem that the profession should assume responsibility for the selection and guidance of young people who presumably could benefit themselves and society by receiving an engineering education, should determine the content and standards of that education, should assist the graduate in the early years of his professional career and encourage his development as a professional man, should specify what constitutes full professional status and when an individual shall be recognized as a member of the profession, and finally, should establish and enforce a code of ethics and canons of practice.

Intimately associated with professional self-government, indeed from one point of view perhaps a part of it, is the problem of the economic status of the engineer. Much has been said on this subject but it is difficult to point to tangible accomplishments. One gets the impression that the rank and file of the profession are still far from being satisfied with their place in the economic scale. In recent years the problem has been complicated by collective bargaining. The profession seems to have been quite unprepared not only to cope with this problem but even intelligently to advise its members. It seems reasonable to suppose that these matters might have been handled to much better advantage for the individual members as well as for the profession as a whole had there been in vigorous existence the type of organization under discussion. This is not to say that the organization would have been a bargaining agency, because as I understand the legislative enactments and their interpretations this

type of organization would not be recognized as an appropriate bargaining group, and, moreover, I, for one, do not believe that a professional association can use the conventional and traditional methods of collective bargaining and still retain its professional character.

Further discussion of the economic status of the engineer and of related problems such as the not wholly advantageous use of technical manpower in the war effort and the completely inadequate provision for assuring a continued supply of trained technical personnel would serve only to support the major premise stated in the beginning on which there appears to be such general agreement. The fact is that our efforts to take care of some of these things through joint co-operative efforts of existing organizations have been belated, halting, and tragically ineffective. As I see it the question is how soon shall we recognize the weakness and futility of our present position and have the courage and determination to rectify it.

PUBLIC SERVICE AND THE ENGINEER

Self-government of the profession should be directed not only toward the establishment and maintenance of high professional standards and the promotion of the economic and social welfare of the individual member but toward the ultimate goal of enlightened and gratuitous public service. Many engineers are more particularly concerned with this broad objective. Again the opportunities and needs in this field have been much discussed but little tangibly has been accomplished.[2,8-12]

Proceeding on the theory of learning to walk before we run, recent efforts in this field have been wisely directed principally to local community problems.[9,13-15] Here again I believe an objective observer would conclude that more rapid progress would be made and the influence of the profession would be stronger if our efforts were not handicapped by the ponderous amenities of interorganizational relationships. From an ideal point of view, which is where we started, it is difficult for me to see how there can be any doubt of the greater constructive influence of the engineering profession in local communities, in states, and in the nation, were it organized to speak for the profession on civic and professional problems with one voice and promptly, as occasion requires.

There does not appear to be the same urgency for bringing together engineers in one organization for the purpose of pursuing to greater advantage their technical objectives. Probably the reason for this is experience has shown that these objectives can be pursued successfully without too great mutual interference. To be sure, many will recognize the need for a greater degree of co-ordination of effort than sometimes obtains but on the whole the situation does not present as serious a problem. Nevertheless, it would seem wise to discourage further subdivision into more highly specialized technical societies and to promote the reunion of the specialized groups in related fields. It is conceivable that the existence of a strong organization of engineers as members of one profession rather than as specialized technicians would help to stabilize the technical societies. However, in my opinion, the latter should be completely autonomous.

In contrast with what I have suggested with respect to the membership of the basic professional organization, namely, that there should be just one class of membership consisting of those who are recognized by the profession as being in fact engineers, the technical societies might advantageously continue a plurality of grades of membership based on age, education, professional status, employment in related fields, distinguished service, or any other criteria that seem good to them. But I would earnestly recommend that in every technical society there be one grade of membership called by the same name and open only to those individuals who are recognized by the basic professional organization as being engineers, although not restricted to members of that organization. It seems to me that, if we are ever to bring an end to the confusion as to who or what is an engineer, we must do something about it ourselves in our own membership nomenclature and in our method of recognition of that status.

Of course, I am assuming that the several technical societies will, by common consent, leave to the basic engineering organization all those activities which I have suggested as being a part of its reason for existence. If we expect to get anywhere we must stop getting into each other's way.

There are still a great many who very sincerely favor the idea of some form of joint activity of the existing organizations, some form of "league of nations" of the engineering societies, or a plurality of such leagues at various levels. I expect that those viewpoints will be adequately presented.

In our consideration of the kind of organization best suited to our purpose, a federation of autonomous societies or an independent society of individual members, I suggest that we ask ourselves these questions:

1. If a federation at the national level is decided upon who will represent us in a particular state on matters peculiar to or confined to that state and who will be our voice in a city or county on local problems?

2. Can a federation of groups having a diversity of primary objectives in specialized fields function as expeditiously and efficiently on a matter of common civic or professional concern as an organization composed of individuals and devoted exclusively to that field?

3. Has human nature changed to such an extent in the past 25 years that the present generation of engineers can hope to function through a federation more successfully than their predecessors, or would we now, with the lesson of the past 25 years before us, be wiser in trying another method which already gives definite promise of success?

4. Which type of organization can speak more authoritatively for engineers, a federation composed of a number of autonomous societies whose membership includes many nonprofessional persons, or a single society composed exclusively of engineers?

5. Which type of organization will be most likely to stimulate the individual members to active participation in the solution of our common civic and professional problems, a federation on the national level somewhat remote from the individual or an organization composed of individuals and built on the active participation of the individual in his local chapter, in his state society, and in his national society?

Many changes can be rung on these five questions but I believe you will find that they cover the field of choice which we must make.

"FEDERATION" IDEA UNSUCCESSFUL

We have tried the "league of nations" idea. It was not too successful. In the light of that experiment so recently concluded I am in favor of trying another method. I commend to the present-day proponents of a federation of the engineering societies that they read the recorded accounts of the formation of the Federated American Engineering Societies which they will find published in the journals of their respective organizations for the year 1920.

That federation was launched with much more fanfare than engineers are usually able to muster for their activities. Those were the days when, because of the accomplishments of engineers in World War I, there seemed to be an opportunity to ride the crest of the wave of public approbation of and admiration for the accomplishments of the engineering profession and of its individual members. The whole thing seemed to reach a climax in the leading editorial of the *Washington Herald* for November 20, 1920, in which the editor opined:

"When the history of the year 1920 comes to be written by chroniclers and interpreters of its important events they will say that the formation in this city of the American Engineering Council of the Federated American Engineering Societies was epoch marking. Conceived during the war, born during a period of reconstruction, it has within it even as a child among institutions, a power that statesmen, politicians, taxpayers, and plain folk must reckon on as henceforth important.

"The persons who are affiliated with this newly constituted council are experts as compared with ordinary civilians or public officials. As human beings, taxpayers and democrats, they are weary of the unnecessary costs, the bureaucratic tyrannies and futilities and the nonrepresentative methods of carrying on public business. They learned

their lesson during the war while aiding the government to function. That which they then learned they are bound all their fellow countrymen shall know. If the latter profit by the instructions and advice well and good. But as for the engineers they are out to fight to the bitter end to conserve national wealth, facilitate cheap and swift transportation of goods and passengers, pacify warring capital and labor, co-ordinate governmental machinery, and make the proved facts of applied science count for more with the average American citizen than the imaginative eloquence of the political orator or the subtly perverted instruction of the hired journalist."

In the light of the sequel, comment would seem to be superfluous. Suffice it to say that the Federated American Engineering Societies and American Engineering Council, its administrative agency, were quietly laid to rest at the tender age of 20 years; immediate cause of death —malnutrition.[15]

I commend to any of you who are inclined to be convinced by the arguments of those who advocate federation that you go to a library if your own files of your respective journals do not go back to 1920 and read there all the pros and cons, but mostly pros as is only natural in a journal of a society favoring a particular type of action, regarding a federation of autonomous engineering societies. That there were doubters in those days is evidenced by the lengths to which some of the pros went to demonstrate that such a federation would be representative and democratic, that it would have the advantage of fine prestige, and that local organizations would be represented adequately. Considerable was written to prove that the organization would not be unduly cumbersome in its functioning. One of the opposing prophets was quoted anonymously before his argument was demolished. I quote him because he was a better prophet than he knew:

"The engineers of the United States today number at least 100,000—possibly 200,000. Within a decade or two it is not impossible that this may be increased to 500,000. Anything short of an effort to bring every one of these engineers individually into the fray by giving them a direct vote and otherwise, would be in the first place to go counter to every modern tendency in democratic theory, but of even greater immediate importance, it would deprive the new federation of the most obvious means of educating and gradually enthusing the rank and file. This is just the kind of opportunity which was missed in the failure to provide that the members of the American Engineering Council should be elected by the votes of the members of the constituent organizations rather than by the boards of these organizations."

NEW INDEPENDENT ORGANIZATION

Admittedly, a federation of existing organizations is attractive. It has one apparent advantage in that it can claim immediately to speak for not only a representative cross section of the profession but a substantial majority thereof. It can claim to speak for them but the fun begins when it attempts to do so. A new and independent organization, on the other hand, has a long, hard struggle to sell itself to a sufficiently large and representative number of individuals before it can make and support such a claim. When it does arrive at that stage, however, it has a much better chance of making good its claim of representing the views and wishes of its members.

NATIONAL SOCIETY OF PROFESSIONAL ENGINEERS

Fortunately, we don't have to start from scratch. We don't have to organize another new society. Such an organization, the National Society of Professional Engineers, is already in existence and is growing steadily in strength and in influence. It is not perfect. No organization conceived by human beings ever has been perfect. But it is structurally simple and sound, and it is aimed in the right direction. By giving it our support and guidance, we can build it into a great instrument for professional advancement and the development of civic consciousness among engineers. By continuing to talk rather than act, we can let it remain just another engineering society.

Shall we spend another 25 years in debate, in forming and later tactfully trying to discharge joint committees or agencies which have outlived their usefulness, in trying to preserve the *status quo* as between the Founder Societies and the 40 or 400 smaller but uncomfortably vigorous offshoots? Or shall we set our house in order using the lessons of the past as a guide and courageously discarding those traditions, sentiments, or procedures which no longer serve a useful purpose?

NOT A PANACEA FOR ALL ILLS

I am not offering for your consideration a panacea for all the ills of the profession. I am not offering you an easy solution. Quite the contrary. If we should be fortunate enough to have all the qualified engineers in one organization, that in itself would not solve our problem. We must work. We must give. We must shake off the lazy habit of letting George do it. We must recognize the futility of the typically American procedure of passing a resolution or a new law every time a problem arises, and then relaxing in the fond hope that we have solved something.

My proposal does not require affirmative action by any existing organization as such. It simply requires action by individuals and that action can be taken only if you and I as individuals so desire. If you agree with our major premise and if you want to do something about it yourself, here and now, join the National Society of Professional Engineers and take as active a part in its affairs as your time and talents permit. If you have not been licensed to practice professional engineering but are qualified, apply for registration and obtain your license so that you may be eligible for membership in that organization. These are matters of individual rather than group determination and hence are capable of prompt instead of delayed execution.

If enough of us pursue this course, ultimately the technical societies, as a matter of policy, will confine their activities to their primary fields in which they have done such excellent work. In the case of the AIEE, this is "the advancement of the theory and practice of electrical engineering and of the allied arts and sciences." And they will be relieved of the necessity of devoting any of their resources to the halting attempts at cooperative action in those broader fields in which the profession has been so ineffective.

Admittedly, this is a bold proposal, but we must be bold if we are to organize the engineering profession for more effective service to its members and to the public. In submitting this article, it is my deliberate purpose to arouse the active participation of the members of the Institute in discussions which should accelerate our progress toward that goal. We have drifted and compromised far too long. We must act. I have taken the steps outlined here, I believe I am on the right track, and therefore I recommend them to you. What do you think, or better still, what have you done?

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INSTITUTE ACTIVITIES

Summer Technical-Paper Program Announced; Closing Date for Discussion, July 15

With the cancellation of meetings due to travel restrictions the second series of technical papers to take the place of those which would have been presented at the summer meeting are offered for discussion by mail.

Many of the papers available now have important wartime applications, which also will be useful in peacetime. Presented at this time are papers in the following fields of activity: instruments and measurements, air transportation, basic sciences, communication, domestic and commercial applications, electric welding, induction and dielectric heating, electric machinery, instruments and measurements, power generation, protective devices, and power transmission and distribution.

Pamphlet copies of papers, for which abstracts appear in the section immediately following, may be ordered, at prices shown, from the AIEE Order Department, 33 West 39th Street, New York 18, N. Y. Coupon books in five-dollar denominations are available for those who may wish this convenient form of remittance. A convenient order form also is included with the announcement of the "Summer Technical-Paper Program" that is being mailed to members in the United States and Canada.

Pertinent discussion adds greatly to the value of a paper. If you have comments related to the treatment of subject matter in any of the papers, submit your discussion and help advance the profession. Discussions should be mailed in triplicate before the closing date of July 15, 1945, to C. S. Rich, secretary of the technical-program committee, AIEE, 33 West 39th Street, New York 18, N. Y. The papers and approved discussion ultimately will be published in AIEE *Transactions;* most of the papers also will appear in *Electrical Engineering*.

ABSTRACTS • • • •

Air Transportation

45-108—Treatment of High-Altitude Brushes by Application of Metallic Halides; *H. M. Elsey* (*M '44*). *15 cents*. It has been found that the rapid wear of brushes under high-altitude conditions can be prevented by the treatment of the brushes with a suitable metallic halide. Carbon, electrographitic, and metalgraphite brush grades all respond to such treatments. A great many nondeliquescent metallic iodides, bromides, chlorides, and fluorides have been tested and found to prevent brush dusting on the heavy-duty electric units of aircraft. These treatments also have been applied with considerable success to earth-surface machines operating under severe commutating conditions. A mechanism by which this class of chemical compound may react to maintain a satisfactory low-friction film on a commutator is proposed.

45-127—An Interval and Dwell Tester for Bomb-Release-Interval Controls; *T. H. Long* (*M '44*). *15 cents*. The device described is essentially a frequency meter with a scale proportional to the logarithm of 1/frequency and a dwell meter suitable for use on inductively loaded contacts in d-c circuits. It has been found useful in several jobs in military aviation, one of which is described in some detail. An appendix gives a simple analysis of the shape of the frequency-scale distribution obtained.

Basic Sciences

45-121—Ferroinductance as a Variable Electric-Circuit Element; *J. D. Ryder* (*A '40*). *30 cents*. A new empirical equation for the magnetization curve of a steel is used to derive an expression for the inductance of iron-cored coils at all current values. This expression is checked experimentally and then applied to analysis of a-c circuits containing such coils. Methods for obtaining the reactance and effective resistance of iron-cored coils for any current value then are developed. As a check of the methods, the concept of ferroreactance is applied to the ferroresonant circuit and expressions secured for resonant voltage, capacitance, and the value of the critical resistance.

45-137—Eddy-Current Resistance of Multilayer Coils; *T. H. Long* (*M '44*). *20 cents*. A precise and simple formula is derived for the eddy-current loss in a spiral coil wound from flat ribbon and closely surrounded on three sides by iron of negligible reluctance. Results are shown graphically. A comparison is given against an earlier formula based on successive approximations and shows good agreemnt for the range in which the earlier formula is valid; this range is defined. Differences in successive layer lengths are accounted for in a modification of the formula. Approximations are introduced to cover absence of the partial magnetic circuit and the use of round wire. Derivations are given for minimum loss for a number of circumstances. Example applications are given for some of the formulas derived, and derivations are given in detail.

45-138—Resistance and Capacitance Relations Between Short Cylindrical Conductors; *F. L. RoQua* (*M '39*). *20 cents*. A simple formula is developed for the capacitance between two parallel cylindrical conductors of relatively short length compared to the distance separating them in terms of a function of their length, radius, and distance of separation. Tables are included giving values of this function for all values of the argument within the useful range. Application of the generalized relation between the capacitance and resistance of a given configuration of conductors in dielectric or conductive medium respectively and Kelvin's image law to the original formula yields a number of useful formulas covering both resistance and capacitance between two or three cylindrical conductors and between cylindrical conductors and planes. Results calculated by these formulas are confirmed by load tests on a large three-phase water rheostat at Bonneville. The formulas and test indicate that electrode-surface current density on such a rheostat decreases with increase of length of electrode immersed in the conducting medium.

Communication

45-134—The S-Function Method of Measuring Attenuation of Coaxial Radio-Frequency Cable; *Chandler Stewart, Jr. 15 cents*. A new method of measuring the attenuation of coaxial radio-frequency cable is proposed. It consists of short-circuiting one end of a sample about one seventh of a wave length long, connecting the other end to a *Q* meter, and applying the data obtained to a curve to obtain attenuation. Although a knowledge of the characteristic impedance of the cable is required, an error in its value will cause a much smaller error in attenuation results. This method is limited by the design of presently available instruments to frequencies from about one to 100 megacycles.

Domestic and Commercial Applications

45-116—Coincidence-Factor Relationship of Electric-Service Load Characteristics; *Constantine Bary* (*M '43*). *20 cents*. This paper contains a demonstration of the existence in practice of relationships between group coincidence factors and number of consumers, and between group coincidence factors and consumers' load factors. It describes the influence of population habits, community and business practices, weather and other climatic conditions, design of utilization equipment, and method of service control upon the coincidence in the use of service. Empirical relationships are developed from test observation of a large number of consumers of the domestic, commercial, and industrial classifications including data for almost a decade before World War II, during the defense period and the height of war-production activities. The relationships developed are analyzed from theoretical considerations, are formulated in a general manner, and are qualified as to the significance of the quantitative values with a demonstration of the effects of various factors upon the empirical relationships.

Electric Machinery

45-102—Symmetrical Components as Applied to the Single-Phase Induction Motor; *F. W. Suhr* (*A'43*). *25 cents.* This paper is intended to show in detail the application of the method of symmetrical components to the solution of single-phase-induction-motor performance characteristics. According to this method single-phase motor theory follows very closely the simpler case of the balanced polyphase motor theory. The author of this paper is of the opinion that a clearer concept of the physical theory can be obtained from this as contrasted to other methods—either the revolving-field or the cross-field concepts. Several special cases of particular interest are developed. The author has endeavored to demonstrate the versatility of the symmetrical-component method in the solution of single-phase induction motors. The theory is continuous in the mathematical sense in that special cases are set up simply by allowing some parameter to be zero or infinity to fit the physical aspects of the problem. The derivations are general enough so that if R_2 is not the same for the low-frequency positive-sequence rotor currents, as it is for the higher-frequency negative-sequence rotor currents, proper allowances can be made in the calculations.

45-111—Static Voltage Regulator for Rotor Exciter; *E. L. Harder* (*M'41*), *C. E. Valentine* (*M'41*). *25 cents.* This paper describes a new type of static control network for use in a rotating amplifier-type voltage-regulating system. The new network is a circulating-current type contrasted with the less efficient balance-voltage arrangements used previously. Analysis is given of the basic circuit and associated auxiliary circuits. These include a new circuit for securing polyphase response, provision for regulating at constant voltage in spite of frequency variation, and reactive droop compensation. Test results confirm the theoretical analysis.

45-120—Tapered-Thickness Bimetal; *W. B. Elmer* (*A'35*). *25 cents.* The most important properties of flat thermostatic bimetal strips of uniformly tapered width or thickness or both have been analyzed mathematically and the findings are described in this paper. Force and deflection values for such tapered strips may be obtained readily from the well-known standard handbook, formulas for flat strips by the inclusion of coefficients obtainable from conveniently usable charts presented in the paper. A tapered-thickness form having an approximate four to one taper is found to be the best practical embodiment of the thickness-tapered bimetal strip, giving a one-third increase in work per unit weight of material as contrasted with conventional flat strips of uniform thickness. A dual-tapered form has been found especially useful in reducing vibration troubles in slow-acting thermostats, and formulas are given for determining the fundamental frequency of single- or dual-tapered strips of any taper ratio.

45-123—Selsyn Design and Application; *T. C. Johnson* (*M'43*). *25 cents.* New designs of Selsyns and new applications of standard designs and principles greatly have increased the field of use of Selsyn systems in the last few years. A better understanding of the fundamentals and the new developments is necessary. Two basic types of Selsyn systems are described: generator–motor, and generator–control transformer. Representative applications which make effective use of these systems are shown to bring out the design requirements. The variety of servo systems using Selsyn generator–control transformer control (now in almost universal use for military equipment and finding increasing use in industry) is pointed out. The causes and magnitudes of errors in Selsyn systems are discussed. The paper concludes with a discussion of possible troubles and a list of specifications for Selsyn systems to insure satisfactory applications.

45-119—Synchronous Starting of Generators and Motor; *C. Concordia* (*M'37*), *S. B. Crary* (*M'37*), *C. E. Kilbourne* (*M'37*), *C. N. Weygandt, Jr.* (*A'37*). *25 cents.* It becomes necessary on many occasions to start a large synchronous machine by connecting it electrically to a generator with both machines at rest and excited, then starting the generator by applied shaft torque, and pulling up the motor by the electrical synchronous torque developed. This paper presents the results of a study by means of the differential analyzer of this method of starting, together with factory tests. Some of the conclusions drawn from this study are: considerable motor torque can be developed by this method of starting, when the total armature circuit resistance is low; the optimum ratio of motor to generator excitation is such that the normal-speed open-circuit voltage ratio is about 0.8; for each circuit condition there is an optimum value of applied generator torque which will start the maximum motor torque, and it is desirable to have a fairly good amortisseur on both machines, if they are not of solid-pole-face construction.

45-125—Industrial Control: Heating of Shunt-Motor Starting Resistors; *G. F. Leland* (*M'45*), *L. T. Rader* (*M'43*). *20 cents.* This paper presents an analysis of conditions which exist when a shunt motor is started with constant field and one point of armature resistance. The two cases of a constant-torque load and a load torque which varies directly as the speed, together with any system inertia, are treated. General analytical expressions are developed from which curves are obtained with coordinates in dimensionless quantities of current and speed at any time as a function of the initial inrush current, moment of inertia of the system, load torque, and final speed. Curves also are given for the watt-seconds generated in the starting resistor as a function of the circuit and load parameters and time. Expressions and curves also show the magnitude of the second current peak as a function on initial current peak, load current, and switching time.

45-129—Impulse-Failure Detection Methods as Applied to Distribution Transformers; *H. C. Stewart* (*M'36*), *J. E. Holcomb* (*A'41*). *20 cents.* This paper gives the results of an investigation of possible methods of impulse-failure detection with particular reference to transformers of the distribution size. The data presented consist of the following procedures for identifying impulse failures:

1. The examination of voltage waves at various points in the transformer structure for possible changes in shape.
2. The inspection of neutral-current waves flowing through a transformer neutral impedance.

It is shown that observation of the changes in the impulse-voltage wave cannot be depended upon to indicate a fault in distribution transformers but that the observation of a voltage wave across a neutral impedance in which neutral current flows is a relatively simple and effective method of impulse-failure detection. It also is demonstrated that the methods outlined in American Standards *C* 57.2 and 10.122, which utilize normal-frequency excitation and the observation of smoke and bubbles, are completely ineffective as a means of impulse-failure detection. Recommendations are made for the inclusion of the impulse neutral-current method in the test code.

45-130—Guides for Operation of Transformers, Regulators, and Reactors; *AIEE subcommittee on transformers. 30 cents.* This paper was prepared by the transformer subcommittee of the AIEE committee on electric machinery. It presents a complete revision of American Standards Association Recommended Practice *C* 57.3 covering guides for operation of transformers and regulators. The principle information given is on loading of equipment under various operating conditions to give normal life expectancy or moderate sacrifice of life expectancy. Such data are given for transformers having specified characteristics, and the use of Appendixes I and II will enable the reader to calculate similar data for transformers having other characteristics. Application at altitudes greater than 3,300 feet is covered.

Electric Welding

45-104—Line Drop Produced by Various Resistance-Welding Systems; *R. L. Longini. 15 cents.* Resistance-welding machines frequently cause high line drop resulting in objectionable light flicker. A simple formula is given for calculating its magnitude. Various methods of reducing the line drop are discussed and are compared as to results. Among these are operation at 2,300 volts instead of at 220 or 440, use of series capacitors to correct power factor, and use of electronic conversion to produce low frequency, thus correcting power factor and balancing the load on the three-phase line. These various correction means must be considered from a metallurgical as well as an electrical point of view.

45-118—When the Welding Load Outgrows the Distribution Power Supply; *C. N. Clark* (*A'36*), *C. M. Stearns. 15 cents.* Certain voltage limitations are encountered in supplying single-phase welders from a local 2,300–4,000-volt distribution circuit which would not apply in serving the usual three-phase power loads of similar size. The two charts shown in the paper have been useful in choosing a satisfactory method of serving welding loads. Modifications to the power system and customer's installation may eliminate the necessity for a new connection from a higher-voltage source.

Industrial Power Applications

45-107—Design of Induction-Heating Coils for Cylindrical Nonmagnetic Loads; *J. T. Vaughan (A '44), J. W. Williamson (A '43). 25 cents.* Equations are presented for the calculation of the required number of coil turns to match a given power source for solenoidal coils with coaxial cylindrical loads. The equations apply to both solid and hollow loads. A correction factor is established for coil shortness, providing the coil length is equal to or greater than the coil diameter. Also given are equations for power distribution, impedance values, and efficiency. It is shown that for relatively thin-wall hollow loads a definite frequency exists at which maximum power-conversion efficiency is obtained. The accuracy of the calculations is substantiated by experimental results. The development of the equations is shown in the appendixes.

45-106—The Role of Frequency in Industrial Dielectric Heating; *G. W. Scott, Jr. (M '45). 20 cents.* A tendency has developed to look upon frequency as a variable in dielectric heating which may be increased at will in order to increase the rate of heating quite independently of other factors. An attempt is made in this paper to determine the practical upper limit of frequency for large-scale industrial dielectric-heating installations. It is apparent from the analysis that:

1. None of the variables in the heating equation is completely independent of frequency or its effects.
2. As frequency is increased, load capacitance must be decreased to allow tuning and to avoid short-circuiting the generator.
3. At higher frequencies load length must be kept small to eliminate the possibility of standing waves.
4. Increased frequency accentuates the load-shunting effect of stray capacitance and seriously reduces over-all efficiency of dielectric heating.

It appears likely that the frequency band from 10 to 30 megacycles will prove best for large-scale industrial dielectric heating, that is, for load capacitances up to 500 micromicrofarads and for output power as high as 100 kw.

Instruments and Measurements

45-105—A Tachometer-Accelerometer-Vibrometer for Instrument Gyro Testing; *R. M. Lawenson, T. H. Long (M '44). 15 cents.* Tooling up for instrument gyro production required the development of certain items of special test equipment, among them an electronic instrument that combines 1,000-rpm and 15,000-rpm tachometers with a direct-reading accelerometer from −0.9 to −0.45 radians per second per second. The electrostatic coupling between the gyroscope and the measuring instrument does not perceptibly influence the gyroscope. The paper gives details as to circuit performance and calibration procedure and a brief history of the development.

45-110—Heat-Flow Effects in the Resistance-Type Thermometer; *N. P. Millar (A '44). 25 cents.* Specifications for the resistance-type temperature transmitter for aircraft applications are necessarily rigid with respect to accuracy and response. This presents a difficult problem from the viewpoint of testing, since there are several variables that must be controlled for reliability of test results. The most important variables affecting accuracy and response are evaluated for several conditions of test. This paper primarily outlines the fundamental equations that may be used in the solution of steady-state conduction problems, and an expression also is developed that describes the response performance of a typical bulb. The effects of variations in the speed of agitation of the medium being measured on (1) the accuracy of temperature detection and (2) the response time of the element are evaluated.

45-133—Response Time and Lag of a Thermometer Element Mounted in a Protecting Case; *W. N. Goodwin, Jr. (F '13). 25 cents.* A thermometer element contained in a protecting case, as in resistance and bimetal types, exchanges heat with an external medium indirectly through the protecting case. This increases the time of response when it is immersed in a constant-temperature medium and also increases the amount of lag in temperature of the thermometer element behind that of the medium when the latter is changing in temperature. Equations are derived for the temperature of the thermometer element at any time for these two conditions, and both are found to be functions of three time constants of the device. The equations are applied specifically to a resistance thermometer, but in general they apply to any body exchanging heat with a medium indirectly through another body. Equations also are derived and applications made to a resistance-type thermometer for the distribution of temperature, under static conditions, along its stem immersed in a constant-temperature medium, and for the resulting errors. Curves are given for the four conditions, both for a particular resistance-type thermometer, and for the general case as functions of nondimensional parameters based upon the time constants of the device.

45-135—Biased-Core-Current-Transformer Design Method; *Theodore Specht (A '41). 15 cents.* It has been well known that peculiar improvements in performance of a current transformer occurred when it was constructed with two parallel cores with different turns on the cores. Both the ratio error and phase angle are much reduced in value with this construction. It was understood in a general way how the transformer operated, but calculation of performance is complicated by the necessity of solving for the flux density in the two cores simultaneously. This paper develops a method of simultaneous solution that is practical, quite rapid, and has a good degree of accuracy. The method depends on a curve of the magnetizing impedance as a function of the voltage for the cores and a set of equations in which repeated substitution approaches the operating point of each core as a limit. The limitations of the construction are analyzed and a comparison between calculated and test values given. This practical and straightforward method of calculation will make possible a better evaluation of this transformer and determination of its field of use.

Power Generation

45-113—Automatic Regulation of Turbine Generators to Relieve Power-Supply Systems of Steel-Mill Load Swings; *W. W. Eberhardt (M '44), C. W. Harrison, E. F. Kohn, A. G. Darling (M '44). 30 cents.* The transmission of sudden heavy cyclic steel-mill loads over portions of extensive power-supply systems has caused sufficient load-swing disturbances in certain instances to warrant correction. Relief for the external supply system from such conditions has been obtained by a new static-load control which causes the steel-mill turbine generators to accept the variable mill loads with provision for modifying the amount of the enforced load according to available steam pressure. The conditions of the power-supply system, the mill loads, and available mill power supply together with a description of the load control and records of its effects are cited in the paper.

45-114—Automatic Load Control for Turbine Generators; *F. E. Crever (A '27), R. L. Jackson. 20 cents.* This article describes a load control for turbine generators installed on 20,000-kw turbines at the plant of the Tennessee Coal Iron and Railroad Company at Fairfield, Ala., to reduce the load swings imposed on a tie line by a hot-strip mill. Previous to installation of the equipment described, the turbine generators carried load under control of their speed governors and variations in strip-mill load, which are about 20,000 kw, were imposed upon the power-company tie line causing disturbances on the power system. It was desired to develop means of imposing part of the strip-mill load on the Tennessee Coal Iron and Railroad Company generators. The method selected was based upon a static watt-measuring circuit, the output of which is an Amplidyne generator which in turn operates the pilot motor of a hydraulic relay, at the turbine to control the steam admission valves.

Power Transmission and Distribution

45-103—Oil Stresses in Impregnated-Paper Insulation; *J. B. Whitehead (F '12). 75 cents.* The values of the stresses in the oil channels of cable-type impregnated-paper insulation as related to the density of the paper are computed in terms of measured values of dielectric constant. The analysis is extended to the case of the graded cable having papers of two values of density. It is shown that the use of high-density paper alone results in higher oil stresses than those resulting with lower-density paper. It also is shown that in the graded cable the use of denser paper may lead to higher or lower oil stresses, as determined by location and relative radial thickness.

45-115—Lightning Investigations on 33-Kv Wood-Pole Lines; *F. E. Andrews (M '27), G. D. McCann (M '44). 30 cents.* This paper describes a three-year investigation of the lightning exposure and performance of 33-kv wood-pole transmission lines with various types of construction and light-

ning protection. Studies have been made of the characteristics of the lightning surge voltages and flashovers on unprotected lines correlated with the probability of occurrence of sustained power follow. Crest-ammeter-link measurements on lines protected with overhead ground wires and deion protector tubes have provided data on the frequency of direct strokes, the crest stroke currents, the crest magnitude of individual-pole ground leads, and the duty on protector tubes as applied in different ways for line protection. A comparison is given between the relative effectiveness of various types of line protection.

45-126—New Transmission-Line Diagrams; *A. C. Schwager* (*M '37*), *P. Y. Wang* (*A '43*). *20 cents.* In connection with the calculation of performance of transmission lines, various charts have found wide application, the modified Evans and Sels power circle diagrams probably being the most frequently used ones. Recently in conjunction with impedance relaying, impedance diagrams have been introduced. It is shown that these diagrams represent conformal mappings of complex functions. In conjunction with the analysis of conformal mappings, additional information is made available which can be incorporated in the above diagrams, resulting in a reduction in the number of steps necessary to arrive at solutions. To date, there has been lacking a universal transmission-line diagram of sufficient simplicity for general use. A new universal diagram, based on the *ABCD* constants, is developed by the introduction of a more suitable co-ordinate system, from which all the required data for any line can be obtained quickly and without construction.

Protective Devices

45-112—A New Outdoor Air Switch and the Principles Involved in Its Design; *H. W. Graybill* (*M '45*), *J. S. Ferguson* (*A '45*) *15 cents.* The outdoor air switch, with its exposed contacts and moving parts, presents an arduous design problem. Although such switches are used widely, relatively little literature is available concerning their design. This paper discusses the problems associated with outdoor air switches and describes a switch designed to solve them.

Statistical-Methods Applications

45-132—Statistics as an Aid to Engineering Judgment in the Manufacture of Lightning-Arrester Blocks; *Casper Goffman. 15 cents.* A large body of mathematical statistics is now at the disposal of the development, or research engineer, a majority of the methods having been developed in the past 20 years. Much of the work of the engineer ultimately is resolved into the collection and interpretation of data; yet, few engineers are familiar with even the simplest statistical tests, such as "chi square," or "significance of coefficient of regression." In this paper a variety of statistical methods are discussed in relation to a complex manufacturing process, the production of lightning-arrester blocks. It is shown that the statistical method acts in two ways. It may confirm or reject an engineer's judgment.

First Mail Presentation of Papers Completed; Preprint Sale Is Normal

Presentation and discussion by mail of AIEE technical papers completed its first step on May 15, which was the closing date for submission of discussion on the 19 papers which comprised the replacement of the usual North Eastern District technical meeting. The technical meeting normally held had been canceled in line with the government ban on convention travel.

Pamphlet copies of the papers were made available for distribution by mail order for those interested in studying and discussing them. Demand for copies was approximately the same as though a meeting had been held, although it must be noted that convenient order forms were sent to a larger percentage of the membership than when a meeting is held. In accordance with existing publication policy all the papers and discussions will appear in the 1945 AIEE *Transactions*. Some of the papers will appear in the monthly Transactions sections of *Electrical Engineering* and the others, together with discussion, will appear in the December 1945 Supplement to *Electrical Engineering*—Transactions Section, which is produced for the convenience of members who do not subscribe to the *Transactions*.

Two additional groups of technical papers, corresponding approximately to the summer and Pacific Coast technical meetings that have been held in other years, are planned. An announcement of the first of these appears elsewhere in this issue.

1945 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1946, may be submitted by any member in accordance with section 1 of article VI of the bylaws of the Lamme Medal committee, as follows:

> The committee shall cause to be published in one or more issues of *Electrical Engineering*, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers of standing, who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified in the foregoing quotation.

SECTION • • • • • •

Record of Achievement by Schenectady Section

"A History of the Schenectady Section of the American Institute of Electrical Engineers" is the title of an interesting 30-page pamphlet recently published. The story runs from 1898 to 1944 and includes the bylaws adopted in 1916; the amendments of 1927, 1928, and 1930, and appendixes 1–8 inclusive.

The purpose in writing this story was to give an over-all, broad, and authentic record of the most important events and general trends that led to the building of the Schenectady Section.

Well-known personalities come to life again in this 50-year record of a very active Section, such as Charles P. Steinmetz, the first speaker to appear before the newly organized society, called "The General Electric Engineering Society." His lecture was entitled "The Rotary Converter."

Outstanding events are reviewed, such as the founding of the Schenectady–Pittsfield competitions for the purpose of encouraging engineers to stand up in public and deliver papers, and another, the observance of the 50th anniversary of the transformer when William Stanley, its inventer, was honored. Many great men had a hand in the development of the Schenectady Section, which is ever striving for bigger accomplishments in the postwar world.

Powel Says Age of Electricity Due After the War

In a recent speech before the Niagara Frontier Section of the AIEE commemorating the 50th anniversary of the installation of the electric generators at Niagara Falls, N. Y., C. A. Powel (F '41) AIEE president, predicted that electricity would accomplish 100 times as much productive good in the next 50 years as it has in the past half century.

President Powel pointed out that when George Westinghouse installed the first of the a-c generators at Niagara Falls 50 years ago, which was the first major a-c installation, it produced only 5,000 horsepower. Production of 5,000 horsepower from a single machine, he added, was an almost unimaginable achievement 50 years ago, but today a single steam turbine producing electricity generates as much as 250,000 horsepower or 50 times as much. He said further that the complete extension of the benefits of electric power will be a major postwar project. Mr. Powel made his predictions in view of the facts that millions of farm homes are still lighted with oil lamps, much farm water still is pumped drudgingly by hand, and industry itself is daily finding new uses for electric power.

Section and Branch Activities—Annual Report for 1944-45

The accompanying constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1945. Similar information for three preceding fiscal years appeared in *Electrical Engineering* in June 1944, pages 224–5; June 1943, pages 264–5; June 1942, pages 322–3.

Present members of the Sections committee and the committee on Student Branches, supervising the divisions of Institute activities covered by this report, are:

Sections—G. W. Bower, chairman; R. M. Pfaisgraff, vice-chairman; A. C. Muir, secretary; L. L. Boach, O. C. Brill, M. S. Coover, W. E. Enns, C. W. Evans, W. J. Gilson, H. P. Heafer, V. P. Hessler, L. F. Hunt, Frederick Krug, E. T. Mahood, R. G. Porter, C. S. Purnell, and, ex officio, chairmen of all Institute Sections.

Branches—E. W. O'Brien, chairman; R. G. Warner, vice-chairman; L. A. Bingham, M. M. Cory, H. L. Davis, Jr., A. G. Ennis, Everett S. Lee, H. C. Madsen, E. M. Strong, and, ex officio, all Student Branch counselors.

Table I. Section Membership and Meetings During Year Ending April 30, 1945

Section	AIEE Members August 1943	AIEE Members August 1944	Number of Meetings	Average Attendance
Akron	87	104	9	109
Alabama	42	44	4	33
Arizona	37	50	9	52
Boston	575	604	8	173
Electric machinery group			3	87
Insulation group			3	58
Electronics group			3	89
Transmission and distribution group			2	66
Instruments and measurements group			1	96
Central Indiana	132	148	8	83
Chicago	849	869	5	162
Power group			3	105
Industrial group			3	103
Communication group			3	129
Electronics group			3	170
Cincinnati	151	149	8	133
Cleveland	368	390	14	111
Columbus	82	84	8	41
Zanesville Subsection			12	31
Connecticut	361	363	8	102
Dayton	122	173	11	126
Aircraft technical discussion group			8	72
Motor and control technical discussion group			2	50
Denver	186	192	10	68
East Tennessee	134	206	14	66
Technical group meeting			9	13
Erie	71	74	8	55
Florida	136	134		
Fort Wayne	100	107	8	89
Georgia	101	115	7	132
Houston	153	180	9	67
Beaumont Subsection			8	53
Iowa	80	78	7	86
Ithaca	60	65	10	81
Kansas City	143	146	10	52
Electronics group			2	10
Industrial practices group			3	9
Personal development			1	12
Lehigh Valley	189	179	8	71
Los Angeles	548	635	11	170
Aircraft division			5	90
Electronics division			4	88
Louisville	75	75	7	73
Lynn	202	211	8	120
Popular lectures			4	1,015
Madison	75	75	2	35
Rock River Valley Subsection			9	60
Mansfield	68	65	8	104
Maryland	349	381	8	161
Memphis	57	72	11	40
Mexico	57	83	12	86
Michigan	398	404	7	105
Round table meetings			6	61
Industrial power group			2	141
Electronics			1	100
Milwaukee	338	371	15	221
Power applications and control group			3	48
Electronics group			3	44
Electric machinery group			3	40
Transmission and distribution group			4	43
Basic science group			4	39
Minnesota	118	124	12	68
Arrowhead Subsection			6	99
Montana	40	36	7	54
Great Falls Subsection			7	39
Montreal	148	208	16	72
Ottawa Subsection			8	41
Muscle Shoals	23	22	1	
Nebraska	50	51	4	49
Technical lectures			1	
New Mexico-West Texas	48	54	9	53
New Orleans	141	151	7	75
New York	3,586	3,814	3	467
Communication group			5	430
Power and industrial group			6	224
Transportation group (Air, Land and Marine)			2	78
Basic science group			4	75
Illumination group			4	106
New Jersey activities committee			3	110
Niagara Frontier	186	185	9	94
Niagara Falls Subsection			5	35
Technical meetings			1	48
Power systems group			1	18
Industrial practices group			1	10
North Carolina	99	119	1	65
North Texas	164	177	9	75
Oklahoma City	90	100	9	101
Philadelphia	863	892	7	154
Aircraft electrical engineering discussion group			3	54
Instruments and measurements group			3	139
Communication discussion group			4	240
Industrial practice discussion group			3	57
Power systems discussion group			3	84
Electronics discussion group			4	64
Wilmington Subsection			7	76
Electrification of industrial plants discussion group			3	21
Pittsburgh	657	663	9	169
Pittsfield	195	196	6	129
Popular lectures			6	1,333
Portland	177	189	14	103
Electrochemical group			1	46
Communication group			2	58
Transmission and distribution group			1	60
Providence	93	101	8	79
Rochester	121	124	8	93
Communication group			2	71
Luncheon meetings			4	55
St. Louis	295	320	9	118
San Diego	56	74	10	60
San Francisco	601	682	12	269
Technical meetings			7	84
Sacramento subsection			6	92
Schenectady	630	619	10	220
Technical discussion group			1	200
Aviation group			4	123
Electronics group			4	81
Seattle	249	274	13	135
Aircraft technical group			1	46
Sharon	162	135	9	65
South Bend	48	60	11	84
South Carolina	55	47	2	39
Charleston Subsection			2	26
South Texas	50	48	8	41
Spokane	85	103	11	53
Springfield	51	55	9	50
Syracuse	129	126	7	114
Toledo	88	87	10	111
Toronto	379	381	14	215
Discussion group			8	36
Hamilton Subsection			6	46
Tulsa	79	73	9	63
Urbana	77	87	4	203
Illinois Valley Subsection			10	69
Utah	85	79	11	88
Vancouver	98	101	12	75
Virginia	147	147	3	59
Washington	675	707	8	278
West Virginia	38	39	6	43
Wichita	62	74	12	66
Worcester	57	65	7	127
	17,321	18,415	884	

Total Sections, 73 Total attendance, 96,346

Table II. Section Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30		
	1943	1944	1945
Number of Sections	73	73	73
Number of meetings held	598	738	884
Average number of meetings	8.2	10.1	12.1
Total attendance	66,111	83,120	96,346
Average attendance per meeting	112	112.6	109

Table III. Branch Meetings Held During Last Three Fiscal Years

	Fiscal Year Ending April 30		
	1943	1944	1945
Number of Branches	125	125	125
Number of meetings held	942	755	542
Average number of meetings	7.5	6.0	4.3
Total attendance	38,227	24,768	17,137
Average attendance per meeting	40.6	32.8	31.6

Table IV. Branch Meetings Held During Year Ending April 30, 1945

Branch	Number	Average Attendance
Akron, University of	4	17
Alabama Polytechnic Institute	0	0
Alabama, University of	1	11
Alberta, University of	0	0
Arizona, University of	0	0
Arkansas, University of	0	0
British Columbia, University of	0	0
Brooklyn, Polytechnic Institute of		
Day division	22	33
Evening division	0	0
Brown University	0	0
Bucknell University	4	32
California Institute of Technology	6	25
California, University of	12	25
Carnegie Institute of Technology	17	31
Case School of Applied Science	6	28
Catholic University of America	0	0
Cincinnati, University of	0	0
Clarkson College of Technology	1	10
Clemson Agricultural College	1	12
Colorado State College	0	0
Colorado, University of	19	55
Columbia University	7	44
Connecticut, University of	0	0
Cooper Union		
Day division	6	10
Evening division	4	9
Cornell University	10	84
Delaware, University of	0	0
Denver, University of	0	0
Detroit, University of	7	12
Drexel Institute of Technology	0	0
Duke University	16	25
Florida, University of	0	0
George Washington University	3	15
Georgia School of Technology	0	0
Harvard University	0	0
Idaho, University of	9	11
Illinois Institute of Technology	7	50
Illinois, University of	1	41
Iowa State College	10	55
Iowa, University of	0	0
Johns Hopkins University	1	20
Kansas State College	8	32
Kansas, University of	5	33
Kentucky, University of	4	10
Lafayette College	8	13
Lehigh University	8	27
Louisiana State University	1	48
Louisville, University of	12	31
Maine, University of	0	0
Manhattan College	0	0
Marquette University	6	28
Maryland, University of	5	26
Massachusetts Institute of Technology	6	74
Michigan College of Mining and Technology	0	0
Michigan State College	3	7
Michigan, University of	15	30
Milwaukee School of Engineering	4	17
Minnesota, University of	3	49
Mississippi State College	0	0
Missouri School of Mines and Metallurgy	2	13
Missouri, University of	0	0
Montana State College	0	0
Nebraska, University of	8	40
Nevada, University of	2	12
Newark College of Engineering	5	37
New Hampshire, University of	0	0
New Mexico State College	0	0
New Mexico, University of	7	37
New York, College of the City of		
Day division	10	41
Evening division	0	0
New York University		
Day division	1	14
Evening division	3	15
North Carolina State College	8	25
North Dakota Agricultural College	0	0
North Dakota, University of	0	0
Northeastern University	9	24
Northwestern University	0	0
Norwich University	0	0
Notre Dame, University of	1	16
Ohio Northern University	0	0
Ohio State University	0	0
Ohio University	0	0
Oklahoma Agricultural and Mechanical College	0	0
Oklahoma, University of	2	70
Oregon State College	8	28
Pennsylvania State College	2	30
Pennsylvania, University of	6	17
Pittsburgh, University of	13	31
Puerto Rico, University of	0	0
Pratt Institute	5	16
Princeton University	0	0
Purdue University	0	0
Rensselaer Polytechnic Institute	1	31
Rhode Island State College	0	0
Rice Institute	24	34
Rose Polytechnic Institute	1	13
Rutgers University	0	0
Santa Clara, University of	1	14
South Carolina, University of	11	24
South Dakota State College	0	0
South Dakota State School of Mines	1	12
Southern California, University of	19	25
Southern Methodist University	9	21
Stanford University	2	19
Stevens Institute of Technology	0	0
Swarthmore College	0	0
Syracuse University	3	12
Tennessee, University of	3	75
Texas Agricultural and Mechanical College	3	41
Texas Technological College	5	23
Texas, University of	14	44
Tufts College	2	39
Tulane University	9	34
Union College	9	43
Utah, University of	1	24
Vanderbilt University	2	15
Vermont, University of	0	0
Villanova College	8	22
Virginia Military Institute	0	0
Virginia Polytechnic Institute	24	24
Virginia, University of	5	27
Washington, State College of	8	15
Washington, University of	6	57
Washington University	5	15
West Virginia University	0	0
Wisconsin, University of	4	45
Worcester Polytechnic Institute	3	49
Wyoming, University of	0	0
Yale University	5	78

Total—125 Branches

PERSONAL . . . . .

L. A. Hawkins (A '03, M '13) executive engineer, research laboratory, General Electric Company, Schenectady, N. Y., has retired from that position and will remain as consultant in the laboratory. He was graduated from Williams College in 897 and from Massachusetts Institute of Technology in 1899. In 1944 he received the honorary degree of doctor of science from Williams College. In July 1899, he went to work in the engineering and patent department of the Stanley Electric and Manufacturing Company, Pittsfield, Mass. Doctor Hawkins joined the General Electric Company in 1903 as patent attorney, later transferring to the transportation engineering division and in 1912 to the research laboratory. **D. E. Chambers** (A'30, M'41) formerly assistant to director, research laboratory, succeeds Doctor Hawkins to become executive engineer. Mr. Chambers received his bachelor-of-arts degree in electrical engineering from Stanford University in 1927 and the following year the degree of electrical engineer. At that time he entered the employ of the General Electric Company to work in research and subsequently went into the test course and the industrial-control division, where in 1933 he became head of the section on the applications of electron tubes. In 1938 he was made assistant engineer of the transmitter engineering division, and in 1944 he returned to the research laboratory. **R. C. Sogge** (M '35) manager of the customer division, central-station divisions, has been given the additional appointment as assistant manager of the central-station divisions. He received his education at Ohio Northern University, earning the degree of bachelor of law, and at the John Marshall School of Law, receiving the degree of master of law. He joined the General Electric Company, Pittsfield, Mass., in 1916 as a testing engineer in the transformer department and a few months later went to the test department in Schenectady. n 1918 he was commissioned a second lieutenant of aeronautics in World War I, returning to the transformer sales department, Pittsfield, in 1919. In 1925 Mr. Sogge was appointed assistant to the manager of the central-station department in Schenectady, and in 1934 he became manager of the customer division.

H. K. Sels (A '20, M '29) transmission and substation engineer, Public Service Electric and Gas Company, Newark, N. J., has been appointed transmission and distribution engineer. He was graduated from Iowa State College in 1919 and completed the graduate-student course of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1920. At that time he was assigned to the central-station section of the general engineering department of that company. Starting with the Public Service Company in 1923 as engineer in the office of the transmission engineer, he was promoted to assistant transmission and substation engineer in 1928 and in 1938 became transmission and substation engineer. **Theodore Seely** (A '41) assistant transmission and substation engineer electric-distribution department, has been made successor to Mr. Sels. Mr. Seely received his degree from Stevens Institute of Technology in 1923 and then entered the company cadet engineers' course. In 1926 he was assigned to the electric-distribution department, central division. In 1930 he entered the office of the distribution engineer, general office, as assistant engineer, and subsequently was advanced to distribution planning engineer in 1937 and to assistant distribution engineer in 1940, and transferred to the transmission and substation engineer's office as assistant in 1943. **Oscar Bauhan** (M '40) installation engineer, electric-distribution department, succeeds Mr. Seely as assistant transmission and substation engi-

neer. Following graduation from Stevens Institute of Technology in 1923, Mr. Bauhan started with the company as district substation operator in New Brunswick district. He was transferred to the general office in 1924 where, until 1942, he served as engineer and installation engineer for the transmission and substation engineer on the design and construction of substations and switching stations.

Philip Sporn (A '20, F '30) formerly vice-president and chief engineer, American Gas and Electric Service Corporation, New York, N. Y., has been elected executive vice-president of the American Gas and Electric Company and executive vice-president and chief engineer of the operating companies of the American Gas and Electric system. Mr. Sporn was graduated from Columbia University in 1917, and from then until 1919 he was with the Crocker-Wheeler Manufacturing Company, Ampere, N. J., engaged in tests and investigations. In 1919 he became technical assistant to the assistant chief electrical engineer of the Consumers' Power Company, Jackson, Mich. He joined the American Gas and Electric Company in 1920 as assistant electrical engineer and was put in charge of the engineering division of the electrical-engineering and construction departments of the company in 1923. He was made chief electrical engineer for these departments in 1927, in 1932 was appointed chief engineer in charge of the electrical and mechanical divisions of the company and its subsidiaries, and was named vice-president in charge of engineering in 1934. When the American Gas and Electric Service Corporation was formed in 1937, Mr. Sporn was elected director and vice-president and chief engineer of that company. Mr. Sporn has been active as a member of the AIEE committees on research, production and application of light, power generation, transmission and distribution, technical program, and Standards, and is now serving on the Lamme Medal committee. He is also a fellow of the American Association for the Advancement of Science and a member of the American Society of Mechanical Engineers and the American Society of Civil Engineers. He is now acting as consultant to the War Production Board. Mr. Sporn is the author of numerous technical papers.

R. H. Manson (A '02, F '44) vice-president and general manager, Stromberg-Carlson Company, Rochester, N. Y., has been elected president of the company. He was graduated from the University of Maine with the degrees of bachelor of science in electrical engineering in 1898, electrical engineer in 1901, and doctor of engineering in 1933. Doctor Manson was employed by the Western Electric Company, Chicago, Ill., in 1899 in the telephone switchboard and later the laboratory departments, and in 1900 he was associated with the Kellogg Switchboard and Supply Company, Chicago, first as laboratory assistant and finally as sales engineer. In 1904 he became assistant chief engineer for the Dean Electric Company, Elyria, Ohio, and subsequently was appointed sales manager in 1908, assistant chief engineer in 1910, and chief engineer in 1912, remaining in that position for the Garford Manufacturing Company, successor to the Dean Electric Company. Doctor Manson joined the staff of the Stromberg-Carlson Company in 1916 as chief engineer, was elected a director in 1920, and became vice-president in charge of engineering in 1924 and general manager in 1940. He is a director of the Radio Manufacturers Association; a fellow of the Radio Club of America, and a member of the Rochester Engineering Society. Doctor Manson is credited with a number of inventions in the field of communications.

J. P. Jollyman (A '05, F '30) hydroelectric and transmission engineer, Pacific Gas and Electric Company, San Francisco, Calif., has retired from that position, and his services will be retained in an advisory capacity. A graduate of Stanford University in 1903 with the degree of bachelor of arts, Mr. Jollyman at that time became electrician, foreman, and superintendent of electrical construction, for the California Gas and Electric Corporation, and in 1909 he accepted the position of superintendent of the hydroelectric plant and electrical engineer for the Great Western Power Company of San Francisco. Both of these companies later were absorbed by the Pacific Gas and Electric Company. In 1911 he returned to the latter company as engineer of electrical construction, and in 1920 was given the title he held at the time of his retirement. In 1937 Mr. Jollyman was elected vice-president of AIEE, representing the Pacific District (8). He has been a member of the committees on power stations (now power generation), power transmission and distribution, the special committee on joint conference on student activities of Districts 8 and 9, and is now serving on the constitution and bylaws committee. Mr. Jollyman is known nationally for his contributions in the field of hydroelectric and high-voltage transmission engineering, and is the author of numerous papers on transmission engineering subjects.

Russell G. Warner (A '19, M '20) chief engineer of the United Illuminating Company, New Haven, Conn., was recently elected vice-president of the company. Mr. Warner received from Yale University the degrees of bachelor of philosophy in 1914 and electrical engineer in 1920. From 1914–16 Mr. Warner was associated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in the student course and later as switchboard-section diagram engineer. In 1916 he became an instructor in electrical engineering at Yale University, New Haven, and continued in that assignment until 1939 when he was appointed engineer in charge of special work for the United Illuminating Company. In addition to his affiliation with that company he was also electrical engineer for the Connecticut Public Utilities Commission (1930–39) and has been consulting engineer for various companies. He was chairman of the AIEE Connecticut Section (1931–32), and served on the education (1924–25), electrical-machinery (1931–33), and Standards (1937–39) committees. In 1942 he served as an AIEE director and as a member of the executive committee, and the committee on domestic and commercial applications. He was appointed chairman of the AIEE committee on Student Branches for 1942–43.

E. L. Phillips (M '26) chairman of the board, Long Island Lighting Company, New York, N. Y., has retired. He was graduated from Cornell University in 1895 with the degree of mechanical engineer, following which he entered the employ of the DeLaval Separator Company, New York, as a draftsman. The following year he transferred to the Sprague Electric Company, which was later part of the General Electric Company, Schenectady, N. Y., where he served as draftsman and designer. In 1897 Mr. Phillips became associated with Westinghouse, Church, Kerr, and Company, New York. He remained with that organization until he established his own consulting engineering firm in 1905 under the name of E. L. Phillips and Company, with headquarters in New York. Mr. Phillips was one of the founders of the Long Island Lighting Company in 1911 and held the position of president of that company for more than 25 years. He also served at one time as president of the Empire Power Corporation, New York, and the Kings County Lighting Company, and as chairman of the boards of Queens Borough Gas and Electric Company, United Gas and Electric Corporation, and United Gas Engineering Company, all of New York.

A. S. McAllister (A '02, F '12) assistant director, National Bureau of Standards, Washington, D. C., has retired. Doctor McAllister was graduated from Pennsylvania State College in 1898 and received the degrees of master of arts (1901) and doctor of philosophy (1905) from Cornell University. In 1898 he entered the employ of the Berwind-White Coal Mining Company, Windber, Pa., gaining experience in electric-locomotive operation and repair, and in that same year went to the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., to work with the manufacturing details of d-c and a-c machinery. From 1901 until 1904 he held the positions of assistant and instructor in physics and applied electricity at Cornell University, Ithaca, N. Y., and in 1904 was appointed acting assistant professor of electrical engineering. In 1905 he became associate editor of *Electrical World*, New York, N. Y., and in 1912 was promoted to editor. Doctor McAllister became associated with the Bureau of Standards in 1921 as liaison officer, in 1936 became head of the division of specifications, and was later made assistant director in charge of the commercial standardization group.

M. L. Manning (A '36, M '42) formerly associate professor of electrical engineering and director of the high-voltage research laboratory, Cornell University, Ithaca, N. Y., has been appointed assistant chief engineer, Kuhlman Electric Company, Bay City, Mich. After graduating from South Dakota State College in 1927, Mr. Manning entered the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., as a student in the graduate-student training program. The following year he was assigned to the industrial-motor division of that com-

pany as a design engineer. In 1932 he obtained the master-of-science degree in electrical engineering from the University of Pittsburgh and in that same year joined the staff of its mathematics department at Pittsburgh as an instructor. He was assigned in 1936 to the transformer division of the Westinghouse Electric and Manufacturing Company, Sharon, Pa., and in 1937 was appointed Westinghouse lecturer in electrical engineering on the staff of the University of Pittsburgh. In 1942 he became associate professor of electrical engineering, Illinois Institute of Technology, Chicago, and in 1943 was appointed to the staff of Cornell University.

G. H. Welch (A '43) assistant manager, switchboard engineering department, Westinghouse Electric Corporation, East Pittsburgh, Pa., since August 1944, has been appointed assistant to the manager of the switchgear and control division. In his new capacity he will continue to direct the company's negotiation, engineering, and production activity on Navy switchboards and similar material and, in addition, will coordinate Navy and Maritime control, commercial control, and other contracts. After one year's service as electrical tester at the Western Electric Company's Hawthorne plant in Chicago, Ill., Mr. Welch went with the Westinghouse Electric and Manufacturing Company in 1924. As a draftsman he did wiring-diagram work in the switchboard engineering department until 1929 when he was transferred to the industrial and central-station switchboard engineering. In 1940 he was made head of the Navy-switchboard design section. Two years later Mr. Welch received the Westinghouse order of merit.

C. H. Willis (A '22, F '42) professor of electrical engineering at Princeton University, Princeton, N. J., will serve as chairman of the electrical-engineering department in a new program of instruction and research in plastics. Doctor Willis received a bachelor-of-arts degree from the University of Richmond in 1914, and a bachelor-of-science degree in engineering from Johns Hopkins University in 1916. After his services with the Signal Corps in World War I he became acting professor of physics at the University of Richmond and in 1920 became associate professor. In 1922–23 he was a graduate student at the Johns Hopkins University and professor of applied physics at the University of Richmond from 1920 to 1925. In 1925 he was a graduate student at the Johns Hopkins University being graduated in June 1926 with the degree of doctor of philosophy. From 1926 to 1929 he served as assistant professor of electrical engineering at Princeton University and as associate professor until 1936, when he became professor.

A. L. Davis (A '17, M '31) assistant general superintendent, Western Massachusetts Electric Company, Turners Falls, Mass., has been named general superintendent. Mr. Davis was graduated from the University of Maine and gained his early experience with the Hydro-Electric Company, Bangor, Me., where he was first employed as assistant engineer and subsequently became acting and then chief engineer. In 1928 he accepted the position of assistant superintendent of distribution for the Alabama Power Company, Birmingham, and in 1930 became associated with the Western Massachusetts Companies as assistant general superintendent. **J. L. Hyland** (M '40) general foreman, station maintenance, has been appointed assistant superintendent of the central division. Mr. Hyland has been associated with the Greenfield (Mass.) Electric Light Company and the Turners Falls (Mass.) Power and Electric Company, as electrician, electrical foreman, resident electrical engineer, general foreman, and superintendent of the electrical maintenance and construction department.

O. S. Schairer (M '13) vice-president in charge of laboratories, Radio Corporation of America, Princeton, N. J., has been elected staff vice-president and will act as consultant on matters pertaining to research, development, patents, trade marks and licenses. Mr. Schairer was graduated from the University of Michigan with the degrees of bachelor of arts in 1901 and bachelor of science in electrical engineering in 1902, and became associated with the corporation as director of the patent division in 1929. **C. B. Jolliffe** (M '34) vice-president and chief engineer, Victor Division, Camden, N. J., has been elected to succeed Mr. Schairer. Doctor Jolliffe received the degrees of bachelor of science (1915) and master of science (1920) from West Virginia University. He joined the corporation in 1935 as engineer-in-charge of the frequency bureau, and subsequently was appointed chief engineer of the laboratories, assistant to the president, and chief engineer of the Victor Division.

I. M. MacLean (A '21) central-station engineer, Canadian General Electric Company, Ltd., Toronto, Ontario, Canada, has been appointed central-station-division manager, in the reorganization of the former apparatus-sales department. A graduate of the University of New Brunswick, Mr. MacLean became associated with the company as a testman in the electrical testing department in 1919. **R. H. Hopkins** (A '08) electrical engineer, becomes manager of the renewal parts and order division. Mr. Hopkins was graduated from the University of Toronto and first became employed with the company in the armature department in 1905. **J. H. Ratcliff** (A '41) district service engineer, contract service department, has been named manager of the transportation division. A graduate of the University of Toronto, Mr. Ratcliff was first associated with the company in 1922 as a test student, and again in 1926 as district service engineer.

R. A. Hentz (A '14, F '29) electrical engineer, Philadelphia (Pa.) Electric Company, has retired after an affiliation of 33 years. Mr. Hentz was born in New York, N. Y., on April 16, 1889. At Cornell University, he specialized in electrical engineering and was graduated in 1911 with the degree of mechanical engineer. In that same year he went with the Philadelphia Electric Company, at first working in the distribution department. Two years later he went into the design division of the station electrical design and construction department and from 1916 to 1920 was in charge of that division. From 1920 he served as assistant electrical engineer in charge of the station electrical design and construction department until October 1925 when he was made electrical engineer in charge of the department. He has served as a member of the AIEE protective-devices committee.

S. B. Way (A '03, F '38) former president, Wisconsin Electric Power Company, Milwaukee, has been elected chairman of the board of directors. After graduating from the Drexel Institute in 1896, with a degree in electrical engineering, Mr. Way was employed by Electric Storage Battery Company, Philadelphia, Pa., as draftsman and erecting engineer. In 1898 he became chief electrical engineer and superintendent for the Imperial Electric Light Heat and Power Company, St. Louis, Mo., and continued in the same capacity for its successor, the Union Electric Light and Power Company. In 1911 he was appointed assistant general manager for the Milwaukee Electric Railway and Light Company, which later became the Wisconsin Electric Power Company; subsequently became vice-president and general manager in 1914; and in 1925 was elected president.

R. M. Smith (A '35) development engineer of the Pacific Electric Manufacturing Corporation, San Francisco, Calif., has recently been added to the engineering staff of the Railway and Industrial Engineering Company, Greensburg, Pa. He will have charge of distribution engineering. Mr. Smith was graduated from the University of Washington in June 1925 with a bachelor of-science degree in electrical engineering. In that year he became associated with the Westinghouse Electric and Manufacturing Company, working in the engineering department at East Pittsburgh, Pa. He also has been identified with the Bryant Electric and Roller-Smith companies, both of New York, N. Y. Mr. Smith was a member of the AIEE instruments- and-measurements committee and is now serving on the protective-devices committee.

Roy Wilkins (A '16, F '29) hydroelectric and transmission engineering department, Pacific Gas and Electric Company, San Francisco, Calif., has joined the staff of engineering consultants of the Bonneville Power Administration. Mr. Wilkins, who was called from retirement in 1941 to supervise emergency power-plant design for the Pacific Gas and Electric Company, has been associated with General Electric Company, Schenectady, N. Y.; Associated Oil Company, Bakersfield, Calif.; and the Pacific Electric Manufacturing Company, San Francisco, where he was vice-president in charge of engineering.

G. E. Rolston (A '30) chief engineer, Rome (N. Y.) Cable Corporation, has been elected to the company's board and made a vice-president. Mr. Rolston, who was graduated from Morningside College in 1923, was employed first by the United Gas Improvement Company, Philadelphia, Pa., and later joined the staff of the General Cable Corpora-

tion as Philadelphia district sales engineer. He was transferred to Rome in 1930 and to New York, N. Y., in 1934. When the Rome Cable Corporation was formed in 1936, he became its chief engineer. He is a member of the technical-advisory committee of the War Production Board.

Newton Jackson (A '14, M '17) former electrical engineer, engineering department, Virginia Electric and Power Company, Charlottesville, has been appointed substation design engineer in the system engineering department of the company at Richmond, Va. **R. C. Bailey** (A '23, F '37) lieutenant commander, United States Naval Reserve, who has been serving on active duty, and was formerly operating electrical engineer of the company at Richmond, has been named electrical engineer in the system engineering department at Richmond.

J. A. Wood (M '36) engineering department, long-lines department, American Telephone and Telegraph Company, New York, N. Y., has been transferred to the transmission section of the plant engineering division. After graduation from Georgia School of Technology in 1925, Mr. Wood began as an employee for the company in Atlanta, Ga., and became associated with the New York office in 1928.

W. R. Harmer (A '37, M '44) supervising industrial engineer, sales-promotion department, Hydro-Electric Power Commission of Ontario, Toronto, Ontario, Canada, has been appointed acting secretary of the Ontario Association of Municipal Electrical Utilities.

OBITUARY • • • •

Charles Edward Waddell (A'02, M'08, F'12) consulting engineer, and builder of many steam and hydraulic plants along the Eastern Seaboard and the western part of North Carolina, died in Asheville, N. C., on April 20 of injuries suffered in an automobile accident on the day previous. He was born in Hillsboro, N. C., on May 1, 1877, and received his education at the Bingham Military School and in the shops of the General Electric Company, working in Bangor, Me., and in Asheville. He received the degree of doctor of science from the North Carolina State College in 1925. From 1897 until 1900 he served as superintendent of the Asheville and Biltmore Street Railway in Asheville. When in the latter year the General Electric Company consolidated the electrical interests in Asheville, Doctor Waddell re-entered its employ as engineer in charge of tracks. A year later he accepted the position of engineer for the Biltmore Estate. This affiliation was followed by numerous others in which Doctor Waddell served as consulting engineer, especially in the electric power and light field. Among his many accomplishments was the designing and building of the North Carolina Electric Power Company's system in Asheville, and his consulting services to the power section of the Council of National Defense in surveying and analyzing the power resources of the southern states for the war emergency of 1917. Doctor Waddell was chairman of the AIEE North Carolina Section in 1936, and a member of the AIEE transmission-and-distribution committee, 1914–16 and 1920–21.

James Daniel Donovan (A'39) manager, production and distribution, Board of Public Utilities of the City of Kansas City, Kans.; president of the American Public Power Association, Washington, D. C.; and president of the Kansas Association of Municipal Utilities, died December 20, 1944, in Kansas City, Kans. Mr. Donovan was born in Kansas City, Mo., in 1885. From 1903 until 1908 he was associated with the Mathews Machine Works, Kansas City, Mo., as mechanical draftsman and assistant shop foreman. The work here consisted principally of designing and manufacturing small gasoline engines. From 1909 until 1916 he was employed by the Atchison, Topeka, and Santa Fe Railway, first in the operating department of the Los Angeles and Valley divisions, and later in the electrical department. He went to the Kansas City, Kans., municipal utilities in 1916 as chief engineer of the power plant. Later he became superintendent of the light department, and chief engineer of the water department. When in 1929 a board of public utilities was created to administer the city's utilities, now including water, power, and airport, Mr. Donovan was appointed manager of production and distribution, a post he held until his death.

Carl Falster Hanson (M '37) chief consulting engineer (sales department) of the Irvington (N. J.) Varnish and Insulator Company, died on April 27, 1945, in Westfield, N. J. He was born in Arkansas City, Kans., in 1884, and received the degrees of bachelor of science and master of science in electrical engineering from the University of Kansas in 1912 and 1913, respectively. From then until 1918 Mr. Hanson was associated with the National Bureau of Standards, Washington, D. C., as laboratory assistant and as assistant physicist. In June 1918 he entered the employ of the Habirshaw Electric Cable Company, Inc., Yonkers, N. Y., as research director where he remained until 1927. For the next few years he was engaged in oil research with the R. T. Vanderbilt Company, East Norwalk, Conn. In 1930 he became technical director of the Irvington Varnish and Insulator Company. Mr. Hanson was on the AIEE committee on instruments and measurements, 1926–27, and was the author of several AIEE papers.

Arthur Bayley Haddow (M '35) chief electrical and mechanical engineer of the Municipal Board of Naini Tal, United Provinces, India, died recently. Mr. Haddow was born on October 2, 1893, in Glasgow, Scotland, and was educated there at the Royal Technical College. He served an apprenticeship with Haddow and Company, electrical engineers of Glasgow, and with David Rowan and Company, marine engineers and boilermakers of Glasgow. He also served as a marine engineer with the Donaldson Line (steam and navigation company). For three years he was in charge of a power station in Chittagong, Bengal, India, and for more than two years assisted in the operation and management of a steam power station in Allahabad, India. This station was converted from Diesel to steam-turbine power and much of the design and erection was done by him. In November 1931 Mr. Haddow was appointed by the Government of the United Provinces to the post of chief electrical and mechanical engineer to the Naini Tal Municipality. In this capacity Mr. Haddow was fully responsible to the Government for the administration and operation of the entire hydroelectric system and water works.

Alonzo Chandler Bell (A '01) president of the Bell Factory Terminal, Garwood, N. J., died recently in Miami, Fla. Mr. Bell was born in Washington, D. C., on February 16, 1877. A graduate of Cooper Union, he began electric-motor production in Garwood in 1907. He designed the Bell electric motor and was a pioneer in the development of the single-phase and polyphase motors operating without external starting compensators. Mr. Bell also designed and built the factory terminal operated by the Bell Electric Motor Company in Garwood, of which he was president. During the past year this company supplied the United States and allied Governments with heavy-duty lathes and other machine tools of Mr. Bell's design. He was also president of the Powers and Robinson Foundry and Machine Company of Garwood. Mr. Bell was president of the Bell Haven Camp, Inc., in Miami which he built. This camp was accepted by the United States for Army use for the duration of the war. Although retired from active practice in the electrical profession Mr. Bell maintained a deep interest in all electrical developments.

Charles Ray Beall (A '18) chief engineer of the Union Switch and Signal Company, Swissvale, Pa., died February 24, 1945, at Edgewood, Pa. Mr. Beall was born at West Lafayette, Ohio, in 1882, and was graduated from Ohio State University with the degree of electrical engineer in mechanical engineering in 1907. From that year until 1910 he was engineering apprentice and designing engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. For the next six years he served as designing and testing electrical engineer with the Union Switch and Signal Company. In 1916 he was appointed electrical engineer of the company and assistant chief engineer in 1923. Fourteen years later he became chief engineer.

Paul Judson Myler (A '07) retired director and chairman of the board of the Canadian Westinghouse Company, Ltd., Hamilton, Ontario, Canada, died on April 20, 1945. Mr. Myler was born in Pittsburgh, Pa., in 1869. He joined the company in Hamilton in 1896 as secretary, and was named general manager two years later. In 1903 when the firm became known as the Canadian Westinghouse Company he became vice-president. He was elected chairman of the board in 1934, a position he held until his retirement in 1944.

MEMBERSHIP . . .

Recommended for Transfer

The board of examiners, at its meeting on May 17, 1945, recommended that following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Gamble, G. P., supt., power production, Union Electric Co. of Missouri, St. Louis, Mo.
Halperin, Herman, staff engr., Commonwealth Edison Co., Chicago, Ill.
Knapp, F. H., dial equipment engr., Ohio Bell Telephone Co., Cleveland, Ohio
Ku, Yu Hsiu, vice minister of education, Chinese Republic, Chungking, China
MacLeod, H. J., prof. and head of dept. of mechanical and electrical engg., University of British Columbia, Vancouver, Canada
Moloney, T. O., chairman of board, Moloney Electric Co., St. Louis, Mo.
Monseth, I. T., mgr., Westinghouse Electric Corp., St. Louis, Mo.
Moore, L. M., principal engr., Rural Electrification Administration, St. Louis, Mo.
Robley, R. R., asst. to the president, Portland General Electric Co., Portland, Ore.
Schneeberger, G. B., elec. engr., Cleveland Electric Illuminating Co., Cleveland, Ohio
Siegmund, H. D., switching apparatus development engr., Bell Telephone Labs., Inc., New York
Skilling, H. H., prof. of elec. engg., Stanford University, Stanford Univ., Calif.
Young, F. C., vice-president in charge of engg. and research, Stromberg-Carlson Co., Rochester, N. Y.

13 to grade of Fellow

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the national secretary before July 15, 1945 or September 15, 1945, if the applicant resides outside of the United States or Canada.

To Grade of Member

Adams, R. O., Rural Elec. Adm., St. Louis, Mo.
Andrews, R. H., Can. Wire & Cable Co., Ltd., Leaside, Ont., Can.
Armitage, J. G., Elec. Lieut., R.N.V.R., Boston, Mass.
Bandrowski, J. J., Austin Co., New York, N. Y.
Bell, W. C., (Reelection), United Illum. Co., New Haven, Conn.
Brance, J. D., Brance-Krachy Co., Inc., Houston, Texas
Browning, R. L., Victor R. Browning & Co., Inc., Willoughby, Ohio
Burg, V. W., (Reelection), Federal Tel. & Radio Corp., East Newark, N. J.
Clipson, L. T. (Reelection), Thirlwell, Henderson & Marine Elec. Co., Indianapolis, Ind.
Coffman, L., Captain, U. S. Army, Fresno, Calif.
Collins, H. R., Major, U. S. Army, Wright Field, Ohio
Dunham, H. W., Rural Elec. Adm., St. Louis, Mo.
Haigler, E. D., Foxboro Co., Foxboro, Mass.
Hale, F. L., U. S. Marines, Cons., Richmond, Calif.
Harris, J. W., Black & Veatch, Kansas City, Mo.
Hatheway, D. H. (Reelection), Boston Edison Co., Boston, Mass.
Hellebuyck, S. (Reelection), Lieut., U.S.N.R., U. S. Bur. of Ships, Washington, D. C.
Henderson, H. J., Ebasco Serv., Inc., New York, N. Y.
Hultgren, C. D. (Reelection), Southwestern Bell Tel. Co., Kansas City, Mo.
Jansen, L. T., Raytheon Mfg. Co., Newton, Mass.
Kirkby, N. R., Office of Elec. Com., Calcutta, India
Mandeville, G. H., Naval Ord. Plant, Camden, Ark.
Manelli, J. R., Radio Corp. of America, Indianapolis, Ind.
McCormack, H. E., Appalachian Elec. Pr. Co., Charleston, W. Va.
Miles, P. S., W. H. Allen Sons & Co., Ltd., Bedford, England
Montgomery, J. E., Rural Elec. Adm., St. Louis, Mo.
Moyle, E. A. (Reelection), Black & Veatch, Kansas City, Mo.
Polyak, M. U., Soviet Pur. Com., Washington, D. C.
Richardson, W. E., Radio Station KOIN, Portland, Oreg.
Ross, W. J., Jr., Alum. Ore Co., East St. Louis, Ill.
Rockwell, R. J., Crosley Corp., Cincinnati, Ohio
Rogers, A. C. (Reelection), Appalachian Elec. Pr. Co., Charleston, W. Va.
Sanders, T. S., Alabama Pr. Co., Birmingham, Ala.
Sas Jaub, I. C., Gen. Elec. Co., Schenectady, N. Y.
Smith, A. V., Electronic Prod. Co., Mount Vernon, N. Y.
Sprague, R. V. (Reelection), U. S. Bur. of Rec., Boulder City, Nev.
Stange, H. D. (Reelection), Chicago Park District, Chicago, Ill.
Stoker, W. G., Rensselaer Poly. Inst., Troy, N. Y.
Tucker, J. C., Boston Elec. Rwy., Boston, Mass.
Uptegraff, R. E. (Reelection), R. E. Uptegraff Mfg. Co., Scottdale, Pa.
Wagner, G. E., Ohio Crankshaft Co., Cleveland, Ohio
Wakeman, H. R. (Reelection), Portland Gen. Elec. Co., Portland, Oreg.
Wells, H., Cent. Ariz. Lt. & Pr. Co., Phoenix, Ariz.

43 to grade of Member

To Grade of Associate

United States and Canada

1. NORTH EASTERN

Alent, L. H., Signal Corps, U. S. Army, Rochester, N. Y.
Brown, G. M., Gen. Elec. Co., Schenectady, N. Y.
Castenhold, R., Gen. Elec. Co., Schenectady, N. Y.
Estes, O. T., U. S. Coast Guard Acad., New London, Conn.
Gross, V., Templetone Radio Mfg. Corp., New London, Conn.
Harrington, F. C., Westinghouse Elec. Corp., Boston, Mass.
Heath, G. F., Captain, U. S. Army, Warner, N. H.
Johnson, O. W., Stromberg-Carlson Co., Rochester, N. Y.
Lee, G. M., Mass. Inst. of Tech., Cambridge, Mass.
Loesch, W. S., Gen. Elec. Co., Schenectady, N. Y.
Lumb, J. C., Gen. Elec. Co., Schenectady, N. Y.
Motsher, W. C., Gen. Elec. Co., Schenectady, N. Y.
Nettesheim, J. C., Gen. Elec. Co., Schenectady, N. Y.
Ohrn, C. T. (Reelection), Cape & Vineyard Elec. Co., Hyannis, Mass.
Otte, G. W., Gen. Elec. Co., Schenectady, N. Y.
Packard, R. H., Arthur D. Little, Inc., Cambridge, Mass.
Schmidt, Y. W., Cutler-Hammer, Inc., Buffalo, N. Y.
Sotelo, E. M., Gen. Elec. Co., Schenectady, N. Y.
Wentworth, A. M., Gen. Radio Co., Cambridge, Mass.

2. MIDDLE EASTERN

Beck, A. D., Penna. Pr. Co., Sharon, Pa.
Charlton, A. A., Duquesne Light Co., Pittsburgh, Pa.
Cole, C. C. (Reelection), Duquesne Light Co., Pittsburgh, Pa.
Cook, W. P., Duquesne Light Co., Pittsburgh, Pa.
Fagnan, D. A., Phila. Elec. Co., Philadelphia, Pa.
Feil, F. C., Gen. Elec. Co., Erie, Pa.
Fox, J. W., Clark Cont. Co., Cleveland, Ohio
Gear, H. F., Ohio Bell Tel. Co., Dayton, Ohio
Hite, H. F., Toledo Medical Depot, Toledo, Ohio
Hooks, G. M., Westinghouse Elec. Corp., Philadelphia, Pa.
Hubbert, E. C., Phila. Elec. Co., Philadelphia, Pa.
Johnson, H. M., Glenn L. Martin Co., Baltimore, Md.
Krause, F. W., Lieut., U.S.M.S., Chester, Pa.
Lawrence, H. W., Westinghouse Elec. Corp., Sharon, Pa.
Layton, W. M. (Reelection), Westinghouse Elec. Corp., Mansfield, Ohio
Marston, F. M., Bell Tel. Co. of Pa., Pittsburgh, Pa.
Milton, O., Westinghouse Elec. Corp., Baltimore, Md.
Poyntz, B. G., Lieut. Comdr., U.S.M.S., Chester, Pa.
Rajsich, S., Westinghouse Elec. Corp., Sharon, Pa.
Roelof, E. A., Lear, Inc., Piqua, Ohio
Ruth, J. M., U. S. Bur. of Ord., Washington, D. C.
Spector, S., Columbia Elec. Mfg. Co., Cleveland, Ohio
Thompson, E. M., Westinghouse Elec. Corp., Baltimore, Md.
Thorn, R. P., Gen. Elec. Co., Erie, Pa.
Walter, R. J., 608 N. 12th St., Allentown, Pa.
Whelan, F. G., Johns Hopkins Univ., Baltimore, Md.

3. NEW YORK CITY

Cooper, B. C., McGraw-Hill Pub. Co., Inc., New York, N. Y.
Harris, C. B., Fed. Tel. & Radio Corp., Newark, N. J.
Heller, R., Cons. Elec. Motor Co., New York, N. Y.
Joyce, J. L., Wright Aero Corp., Woodridge, N. J.
Kanis, E. R., Bell Tel. Lab., Inc., New York, N. Y.
Kaplan, J. Y., Fed. Tel. & Radio Corp., Newark, N. J.
Oberle, H. J., Gen. Electronics, Inc., Paterson, N. J.
Ribeiro, S. C., Sperry Gyroscope Co., Great Neck, N. Y.
Scholl, C. G., Bendix Avia. Corp., Red Bank, N. J.
Selzo, C. A., Ward Leonard Elec. Co., Mount Vernon, N. Y.
Thurston, E. G., Sperry Products Inc., Hoboken, N. J.

4. SOUTHERN

Brantley, L. D., Tenn. Val. Auth., Knoxville, Tenn.
Eiland, H. A., Gulf Ord. Plant, Prairie, Miss.
Hollandsworth, F., U. S. Navy, New Orleans, La.
Nickles, W. D., U. S. Navy Yard, Charleston, S. C.
Stewart, W. A., Stewart Elec. Serv., Jonesboro, Ark.

5. GREAT LAKES

Arthur, B., Harnischfeger Corp., Milwaukee, Wis.
Bouse, R. C., Detroit Edison Co., Detroit, Mich.
Davis, D. W., Commonwealth Edison Co., Chicago, Ill.
Dequaine, D. C., Allis-Chalmers Mfg. Co., West Allis, Wis.
Evans, F. H., A. G. Redmond Co., Owosso, Mich.
Feldman, F. R., G. Le Tourneau, Inc., Peoria, Ill.
Foss, R. F., Carnegie-Ill. Steel Corp., Chicago, Ill.
Frederickson, J. J., Gen. Elec. Co., Fort Wayne, Ind.
Gaylord, F. W., Amertorp Corp., Forest Park, Ill.
Haverlah, K. W. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Heublein, E. C., Harnischfeger Corp., Milwaukee, Wis.
Knotze, H. L., Ind. Pr. & Lt. Co., Indianapolis, Ind.
Lucas, G. G., Harnischfeger Corp., Milwaukee, Wis.
Miller, C. V., Pub. Serv. Co. of Northern Ill., Joliet, Ill.
Miller, G. H., Esterline-Angus Co., Inc., Indianapolis, Ind.
O'Rourke, L., Cent. Ill. Lt. Co., Princeville, Ill.
Otten, A. J., R. Herschel Mfg. Co., East Peoria, Ill.
Owings, S. B. (Reelection), A. O. Smith Corp., Milwaukee, Wis.
Parsons, H., Westinghouse Elec. Corp., Detroit, Mich.
Percy, W. G., Northwestern Bell Tel. Co., Des Moines, Iowa
Pfeiffer, R. P., Hiram Walker & Sons, Inc., Peoria, Ill.
Pleasants, E. B., Badger Ordnance Works, Baraboo, Wis.
Renken, H., Caterpillar Tractor Co., Peoria, Ill.
Sedgwick, H. T., Amer. Tel. & Tel. Co., Peoria, Ill.
Sprengel, H. J., Gen. Elec. X-Ray Corp., Chicago, Ill.
Streuf, F. E., Gen. Elec. X-Ray Corp., Chicago, Ill.
Tillman, E. L., Int'l. Brotherhood of Elec. Workers, Peoria, Ill.
Tucker, E. M., Altorfer Bros. Co., Peoria, Ill.
Waterman, H. C., Bendix Avia. Corp., South Bend, Ind.
Webb, W. E., Westinghouse Elec. Sup. Co., Peoria, Ill.
Woods, A. J., Defoe Shipbldg. Co., Bay City, Mich.
Zupancic, F. J., Rep. Steel Corp., Chicago, Ill.

6. NORTH CENTRAL

Tarbox, G. E., Manufacturers Agent, Denver, Colo.
Zito, A. F., Kershaw, Heyer, Swinerton & Walberg, Denver, Colo.

7. SOUTH WEST

Allen, H. L., Southwestern Pub. Serv. Co., Lubbock, Texas
Balcom, H. A., Magnolia Pipeline Co., Dallas, Texas
Banks, A. G., Merriam, Kans.
Buck, D. B., Jr., U. S. Navy, Corpus Christi, Texas
Davis, M., Western Union Tel. Co., Dallas, Texas
Euler, P. H., Rural Elec. Adm., St. Louis, Mo.
Francis, G. A., Assoc. Press, Kansas City, Mo.
Garrett, T. M., USAAF, Stephenville, Texas
Heinemann, F. E., Rural Elec. Adm., St. Louis, Mo.
Luechau, C. W., U. S. Cartridge Co., St. Louis, Mo.
Madden, P. R., St. Joseph Lt. & Pr. Co., St. Joseph, Mo.
Soucy, H. A., Southwestern Bell Tel. Co., Fort Worth, Texas
Woodruff, J. R., Elec. Cont. & Mfg. Co., Houston, Texas
Zurheide, C. H., Union Elec. Co. of Mo., St. Louis, Mo.

8. PACIFIC

Astorga, L. T., Calif. Shipbldg. Corp., Wilmington, Calif.
Babcock, A. V. K., Cent. Ariz. Lt. & Pr. Co., Phoenix, Ariz.
Barstad, J. A., North Amer. Avia., Inglewood, Calif.
Buchwald, J. W., Bethlehem Steel Co., San Francisco, Calif.
Crilley, C. D., Pac. Gas & Elec. Co., San Francisco, Calif.
Dickson, C. T., Ariz. Edison Co., Inc., Casa Grande, Ariz.
Guerassimoff, D. B., U. S. Naval Drydocks, San Francisco, Calif.
Kelly, L. D., Gen. Elec. Co., Phoenix, Ariz.
May, J. V., Westinghouse Elec. Corp., Los Angeles, Calif.
Pomo, H. P., Westinghouse Elec. Corp., Los Angeles Calif.
Robinson, H. W., Westinghouse Elec. Corp., Los Angeles, Calif.
Takken, F. R., G. M. Simonson, Cons. Engr., San Francisco, Calif.
Tufford, A. A., Allis-Chalmers Mfg. Co., San Francisco, Calif.
Ward, D. C., North Amer. Avia., Inglewood, Calif.
Warne, V. J., Micro Switch Div., Los Angeles, Calif.
Werden, A. C., Jr., So. Calif. Edison Co., Ltd., Los Angeles, Calif.

9. NORTH WEST

Dusenberry, W. M., Line Material Co., Salt Lake City, Utah
Fragall, A. D., Portland Gen. Elec. Co., Portland, Oreg.
Gold, M. O., Elmco Corp., Salt Lake City, Utah
MacMurray, S., Armstrong Heat Control Co., Portland, Oreg.
Mithoug, O. J. (Reelection), Swett & Crawford, Portland, Oreg.
Parker, G. D., Multnomah College, Portland, Oreg.
Rethmeyer, H. G., Westinghouse Elec. Corp., Seattle, Wash.
Sauke, E. F., Bonneville Pr. Adm., Portland, Oreg.
Singer, C. D., Westinghouse Elec. Corp., Seattle, Wash.
Smith, W. F., Line Material Co., Salt Lake City, Utah
Wohlgemuth, D. G., Bonneville Pr. Adm., Vancouver, Wash.
Young, E. V., Columbia River Paper Mills, Vancouver, Wash.

10. CANADA

Bunston, R. F. E., Elec. Lieut., R.C.N.V.R., Halifax, Nova Scotia
Clarke, E. A. (Miss), Can. Westinghouse Co., Hamilton, Ont., Can.
Dale, G. T., Elec. Main. & Repairs Co., Ltd., Toronto, Ont., Can.

Elsewhere

Bullick, D., Cole St., Dannevirke, N. Z.
Daoud, D. A., Pub. Works Ministry, Mahmoudieh, Egypt
Ghare, Y. B., Cawnpore Elec. Sup. Corp., Ltd., Cawnpore, India
Major, D. F., Ministry of Munitions, Sydney, N. S. W., Aust.
Muncey, R. W. R., Univ. of Melbourne, Victoria, Aust.
Oliphant, W. D. (Reelection), The University, St. Andrews, Scotland
Pathak, S. C., Indian Inst. of Science, Bangalore, India
Quadir, S. A., H.E.H., Pub. Works Dept., Somajiguda, Hyderabad, India
Row, K. B., Indian State Railways, Bihar, India
Subramanian, R., Ordnance Factory, Bombay, India
Traylor, J. D., Metropolitan-Vickers Elec. Co., Ltd., Manchester, England
West, G. W., 37 Nicholson St., Victoria, Aust.

Total to grade of Associate
United States and Canada, 140
Elsewhere, 12

OF CURRENT INTEREST

Ambrose Fleming's Life Spanned Radio's Developments

The death of Sir Ambrose Fleming on April 19, 1945, in Devon, England, at the age of 95, removed a distinguished figure from the field of electricity and radio. He was associated with the introduction to Britain of the telephone, electric lighting, and wireless telegraphy, and designed the wireless signal apparatus of the Marconi station in Cornwall. He was the last of the school of Maxwell, Marconi, and Sir Oliver Lodge, all pioneers of wireless.

As the inventer of the diode valve which made the reception of radio waves sure and easier, he paved the way for Lee de Forest to introduce the grid which made the vacuum tube a highly sensitive device which could turn a stream of electrons on or off and "give the radio engineer anything from a trickle to a Niagara."

In the early 19th century Sir Ambrose prepared a text of more than 1,700 pages covering electromagnetic-wave phenomena which became a bible to radio men and is now considered a classic. Among his works is a text on radiotelephony written at a time when very little was known about "modulating" a space wave with voice or music. These books were used as textbooks for the training of students in the radio–electrical fields and are included in the 90 or more highly important scientific treatises he produced between 1892 and 1934.

Sir Ambrose was educated at University College, the Royal College of Chemistry, and St. John's College, Cambridge.

Statue of Liberty Signalized V-E Day

New lighting more closely resembling an actual flame blazed in the torch of the Statue of Liberty on Bedloe's Island, New York, N. Y., on V-E Day on May 8, 1945. To supply a flame of bluish-white brilliance, engineers of the Westinghouse Electric Corporation, East Pittsburgh, Pa., added six 400-watt high-intensity mercury-vapor lamps to the 13 1,000-watt incandescent lamps and one 250-watt incandescent lamp which simulated the flame before the war. Sixteen special floodlight projectors were also added, each containing a modern quartz-inner-bulb 400-watt high-intensity mercury-vapor lamp. The new mercury-vapor lamps and the incandescent lamps retained in the latest installation are grouped in a cluster which is enclosed by the outer wall of the torch. The wall is made up of more than 600 panes of glazed cathedral glass supported by steel ribs.

Samuel G. Hibben, director of applied lighting for the company, directed the last relighting of the statue in 1931. He submitted a program for the modernization of the illumination late in 1941, but the proposal was deferred because of the United States entrance into the war. Used since that time merely as a warning marker for airplanes and ships, the torch flame which burns 300 feet above New York Harbor was relighted in a mightier blaze as a victory signal and watchtower of peace the day Germany surrendered. On that day the augmented battery of 112 giant reflector lamps at the statue's base was switched on, and a modernized floodlighting system was turned on to full brilliance.

Color Television for the Future

The inevitability of establishment of a color television service was the opinion of L. C. Jesty, speaking before a recent meeting of the radio section of the Institution of Electrical Engineers in England. He reviewed three types of scanning sequences and mentioned methods of producing the necessary primary colors. He believed that the only immediately practicable system was the "sequential-color frame-scanning" system. With regard to the standard of definition Mr. Jesty said that a 405-line color picture would require about three times the video band width, and with vestigial side-band transmission about twice the ether space of the prewar 405-line transmission. On this basis, a 500–600-line color picture was not inconceivable as a long-term development. He gave demonstrations of the synthesis of white light from three primary colors.

In the discussion several speakers commented on the apparent improvement in contrast in the color pictures, and it was agreed that less range of tone was required in color than in a black-and-white system. One speaker thought that a mechanical system of scanning might provide a solution; small high-speed motors were now available with a useful life of the order of 4,000 hours. The chairman concluded that color television is not likely to become an established service for some years, but when it does it will be of great value as there are many subjects which cannot be adequately portrayed in monochrome.

Critical Shortage of Engineers Continues to Be Alarming

To obtain a picture of the present critical shortage of engineering graduates, A. A. Potter, dean of engineering of Purdue University, Lafayette, Ind., sent a communication to about one third of the 400 companies which ordinarily employ engineering graduates of the university and which have been requesting engineers with increasing urgency. The communication, sent to a good cross section of American industry, asked for information on present and future needs. Replies received revealed the following information:

105 companies replied.

8 or 7.6 per cent indicated no need for additional engineering talent.

97 or 92.4 per cent companies, including both large and small industries, reported a total need of 4,590 engineers.

47 was average shortage of engineers per company.

The companies which reported may be listed under the following categories:

Aircraft industries	7
Chemical, rubber, and oil industries	25
Construction companies	3
Electrical manufacturers	18
Machinery and automotive manufacturers	22
Railroads and railway supply companies	3
Steel and other raw-material industries	6
Utilities	6
Miscellaneous	15

"The foregoing survey, which included only a very small percentage of American industries, revealed an urgent need for 4,590 engineers. This would indicate that the total need by American industry of trainced engineers is certainly many times the shortage reported. This is particularly serious since the output of civilian engineers from all engineering colleges of the United States during the present year will be less than 2,000 and will be made up largely of individuals who are physically incapacitated," according to the report.

In addition to their present urgent needs, the companies were asked to indicate their long-range needs after the emergency is over. These long-range needs for 96 companies total 3,509, or 36 engineers per company. These totals will not be affected by the return of veterans since the companies took this into consideration when reporting.

This survey indicates that the United States is now confronted with a critical shortage of engineers. This may prove a serious handicap in expediting the end of the war in all theaters of operation, as production of war equipment is bound to be unfavorably affected by the shortage of engineers who have the knowledge to plan, design, and supervise industrial production.

The ending of the war will find the United States with many of its natural resources greatly depleted and facing from other lands the keenest industrial competition ever conceived. To keep full employment in industry in the years of reconstruction adequate, engineering and scientific staffs must be made available to develop new materials and better articles of commerce, and to manufacture them in large quantities at low cost to meet world competition.

Electricity Generated in Britain. The total quantity of electricity generated at public supply stations in Great Britain in 1944 was 38,354 million units compared to 36,951 million units in 1943, or an increase of 3.8 per cent. The increase since 1939 has been 11,945 million units or 45.2 per cent of the 1939 output. These data are contained in the 17th annual report of the Britain's Central Electricity Board. At the end of 1944 the Grid comprised 5,142 miles of transmission lines. Of these 3,614 miles was operated at 132,000 volts and 1,528 at 66,000 or lower voltages. The Grid also included 348 switching and transforming stations.

Helicopter Blades Protected From Rain. Development of a rubber material to protect high-speed helicopter rotor blades from the abrasive effects of sand and rain has been announced by the United States Rubber Company, Akron, N. Y. The material is a strip of specially compounded synthetic rubber, 18 feet long, which is cemented to the leading edge of each blade. United States Coast Guard pilots testing the material flew their machines many hours in heavy rain without damage to the blades. The rotor blade tips attain a speed of more than 325 miles per hour, bringing strong air pressure against the fabric surfaces.

WAR PROGRAM • •

Learning-to-Fly Classes Formed. Combining their training facilities to provide top-flight efficient crews for the 20 *FRM* Mars, the United States Navy and The Glenn L. Martin Company have begun the first of a series of maintenance and operational classes at the company's plant in Baltimore, Md. According to present schedules, almost half the Navy men will have been trained by the end of the first four months.

Most of the trainees are veterans of flying in other types of heavy Navy transports and flying boats.

The *FRM* courses are being conducted under the direction of Lieutenant Ted W. Turner, United States Naval Reserve, and Frank Fidelman, the school's director. Detailed outlines of the work have been planned on the basis of experience compiled from the records of the Mars's operations between the Alameda and Honolulu bases. The course will combine the merits of both technical and practical training.

POSTWAR • • • • •

To Salvage Science—An Imperative Need

The United States "is headed for a second-and-third-rate role in the postwar period" unless present Government policies of drafting scientific students and of exporting scientific equipment are remedied, according to an editorial in a recent issue of *Industrial and Engineering Chemistry*, published by the American Chemical Society, New York, N. Y.

The editorial entitled, "Shall We Sell America Short Scientifically?" declares that the United States through its selective-service policies already has lost one generation of future scientists and is on the way toward losing a second, even while foreign nations are sending increasing numbers of students to the United States for training to staff research institutions in their home countries. The writer contrasts the unwillingness to defer bonafide students in institutions of higher learning in the United States with the current enrollment of foreign students in this country.

Continuing the indictment of American draft practices, the editorial states further that American manufacturers of equipment, scientific apparatus, and other highly technical commodities, are deluged with orders under lend–lease to be employed in the postwar period for equipping plants and research laboratories in countries with which the United States is now allied in a common war effort, though lend–lease "is supposed to provide an exchange of goods and services for the sole purpose of winning the war."

Evidence of the preferential treatment given to foreign students by their Governments is widespread in the United States according to the editorial. "One of the largest institutions in the United States, which was popular with foreigners prior to World War II, experienced this year an increase in enrollment of 100 per cent in foreign students over the average attendance in the period 1920–39 and has on hand applications representing an increase of over 400 per cent above the 1920–39 period," the editorial states. Mention also is made of the facts that India is sending 250 students holding master's degrees to the United States in 1945, and France is establishing national fellowships in the United States. There is a minimum of 3,256 students from other American republics enrolled in United States colleges and universities. Although such interchange is applauded by the editorial, the contrast with United States policy toward its own scientific students is deplored.

Discusses Developments for Peace. Henry N. Muller, Jr. (M '43) central-station engineer of the Westinghouse Electric Corporation, East Pittsburgh, Pa., and consultant on power-station matters, cited the buzz bomb, the rocket, and the bazooka to illustrate the performance of the jet-propulsion engine in agents of destruction. Speaking before members of the Rochester (Minn.) Rotary Club, he predicted the harnessing of that motive power to useful humane roles in the postwar era. He said that the meteorologist will utilize rockets to take important soundings of the atmosphere 50 or 100 miles above the earth instead of the shallow five or six miles now possible; that jet-propelled aircraft, in production now for military purposes only, offers promise of passenger travel through lofty altitudes at 700 miles an hour in the not-too-distant future. Among the many innovations that have undergone vast improvement under the spur of war, Mr. Muller named the gyroscope, which would make aircraft navigation simpler and safer and bring greater comfort of travelers on our railroads; devices to cleanse dust, dirt, smoke, and disease germs from the air; new types of lamps for heat, health, and better readability, and the insecticide bomb which will go on duty in homes and industry when its wartime duties are finished.

Scholarships for World of Tomorrow. The awarding of 41 new postservice fellowships to men now serving with the United States Armed Forces throughout the world has been announced by the John Simon Guggenheim Memorial Foundation. These are to be ready and waiting for the recipients when the war ends. Thus the progress of the arts and sciences is visualized despite the ravages of war and the loss of leaders of the future capable of advancing the cause of humanity.

Plan for Scientific Research

The cost of mobilizing science during the war was $472,984,799, the sum spent by the Office of Scientific Research and Development for war research. A committee headed by Representative Woodrum supported by Secretaries Stimson and Forrestal has raised its voice for the continuance of military research in the belief that the war could not have been fought without the aid of chemists, physicists, and engineers. This committee would turn the matter over to the National Academy of Sciences which would act through a committee of 40, half officers, half civilian scientists, with a civilian as chairman. This governing committee would control scientific research and development of all branches for the Armed Forces, with the Academy reporting from time to time to the proper committees of the Senate and the House on expenditures, and the president of the Academy paying out funds on vouchers.

War Veteran Gets Jobs for Veterans. In line with its intention to help the rehabilitation of 1,200 members serving in the active forces and a larger number employed in war industry, The Engineering Institute of Canada, Montreal, Quebec, has appointed Major Donald C. MacCallum, a veteran of the campaign in Italy and recently discharged from the army because of wounds, to direct its personnel services. A recent survey indicated that both engineers and their employers expect the Institute to perform this type of service. The Engineering Institute of Canada has had more than 25 years' experience in the placement of technical personnel.

OTHER SOCIETIES •

Instrument Society Formed. A new national society to be known as "The Instrument Society of America" was organized in Pittsburgh, Pa., on April 28, 1945, at a conference attended by delegates of 15 measurement-and-control-instrument societies from different industrial centers throughout the United States. The purpose of the society, which is nonprofessional, will be to advance the arts and sciences that are connected with the theory, design, manufacture, and use of instruments. Pro-tempore officers elected included A. F. Sperry (M '37) owner of the Hubbard Engineering Company, Chicago, Ill.

Street Lighting Called Too Dim

Street lighting in more than 90 per cent of American communities is so dim that it fails to meet even the minimum requirements for safety, according to John L. Kilpatrick, illuminating engineer for the lamp division, of the Westinghouse Electric Corporation.

Speaking before a joint meeting of the St. Louis Electrical Board of Trade and the Spirit of St. Louis chapter, Illuminating Engineering Society, he said that the present average illumination on the business

streets of most cities should be stepped up 20 times. His recommended illumination for business areas is five foot-candles which, Mr. Kilpatrick explained, "is still only one-tenth of the 50 foot-candles which many war-plant workers now enjoy."

Wartime and postwar developments in electric-light sources and equipment will make higher levels of street lighting economically practicable, Mr. Kilpatrick said. Possible postwar applications of two new types of fluorescent tubes, the circular and slim-line, and unusual ideas for using conventional fluorescent tubes were suggested in color slides which Mr. Kilpatrick showed.

Pennsylvania Electric Association Meets. The spring meeting of the transmission-and-distribution committee of the Pennsylvania Electric Association was held at the Brunswick Hotel in Lancaster, Pa., on May 24–25, 1945. The sessions were in the nature of round-table discussions, and the conference subjects included one on high-voltage transmission problems.

HONORS

W. F. Durand Awarded John J. Carty Medal

William Frederick Durand, professor emeritus of Stanford University, Palo Alto, Calif., has been awarded the fifth John J. Carty Medal for the Advancement of Science and an honorarium of $2,500 by the National Academy of Science. The award was made with this citation—"in his profession, a versatile and creative engineer, among his colleagues, a wise and friendly counselor; before his students, a kindly and inspiring teacher; to the Nation, an able and devoted servant."

Professor Durand, a mechanical engineer, and at one time member of AIEE, has written many papers and articles for the technical and engineering press and is the author of "Resistance and Propulsion of Ships," "Practical Marine Engineering," and "Hydraulics of Pipe Lines." He was general editor of "Aerodynamic Theory" in six volumes.

The John J. Carty Fund of $25,000 was established in 1930 by close associates of Doctor Carty when he retired from the vice-presidency of the American Telephone and Telegraph Company. Both the medal and the monetary award are granted for noteworthy and distinguished accomplishments in any field of science coming within the scope and charter of the National Academy of Science and are accompanied by a diploma citing the reasons for the award. It is stipulated that the award shall not be made oftener than once in two years. The first award was made posthumously to Doctor Carty.

Degree Conferred on Aircraft Official. In ceremonies held recently at the Case School of Applied Science, Cleveland, Ohio, the honorary degree of doctor of engineering was conferred upon Glenn L. Martin, president of The Glenn L. Martin Company, Baltimore, Maryland.

INDUSTRY

Rapid Progress on Coaxial-Cable Program of Bell System

By the end of this year the Bell System expects to have 2,000 miles of its coaxial-cable network manufactured and at least three fourths of this mileage in the ground, according to a recent announcement of the American Telephone and Telegraph Company. By the end of this year the cable crews on the new all-cable route to the West Coast are scheduled to be in the vicinity of Fort Worth and Dallas, halfway across the continent. The aim is to reach Los Angeles in the spring of 1947. One year ago the company announced a five-year coaxial-cable program involving 6,000 to 7,000 route-miles of construction.

In addition to its use for long-distance telephone service, coaxial cable is capable of transmitting the very broad bands of frequencies required for television. The coaxial-cable system now being built is therefore suitable to form the backbone of future nationwide television program networks.

Experiments with coaxial systems as a means of transmitting many telephone conversations simultaneously over one pair of conductors began more than a decade ago. Use of the New York–Philadelphia cable for transmitting television images was first demonstrated in 1937.

The coaxial cable itself consists of a copper tube with a single wire in its center. With the present terminal and repeater equipment, a pair of coaxial cables can provide 480 telephone circuits, or, the coaxial cable can be arranged to transmit both the visual images and the accompanying sound for television programs.

The Bell System's projected radio-relay system between New York and Boston is also going forward. This trial of microwave transmission is intended to determine its efficiency, dependability, and economy for multiplex telephony and for interconnecting sound broadcast and television stations. It will help to determine how large a role this type of system will play in the provision of additional links in the Bell System's network of communication routes.

Adventure in Review. As a portal through which readers may glimpse some of the world-wide activities in which the International Telephone and Telegraph Company is engaged, a company publication, *The International Review*, will appear monthly. The first issue, dated April 1945, tells the story of Brazil and gives a roundup of happenings in the company's system and news about promotions and movements of personnel. The editors hope that the readers will discern the spirit of adventure in these pages.

Eisler Has 25th Anniversary. The Eisler Engineering Company, Newark, N. J., is celebrating the 25th anniversary of its founding by Charles Eisler (A '41), chief engineer. Though at first a small plant employing only a few men, it specialized in the design and manufacture of automatic machinery essential to the mass production of incandescent lamps, radio, electronic tubes, and accessories. Prior to establishing his own business, Charles Eisler was for several years employed by Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Inspired by the conviction that anything that could be made by human hands could also be produced on automatic machines faster and better, Mr. Eisler embarked on a series of small-scale experiments which proved that radio tubes could be made on machines. Notable among his inventions is the bent exhaust-tube process for making tipless house lamps. To commemorate the 25 years of pioneering research, the company announces a special anniversary catalogue containing information and technical data for the electronic glass-working industry.

Air-Conditioning Department Formed. Establishment of the air-conditioning department as one of the operating departments of the General Electric Company, Schenectady, N. Y., has been announced. Operations pertaining to heating, air conditioning, and commercial refrigeration previously were the responsibility of the appliance and merchandise department. The new department will have its headquarters at Bloomfield, N. J., and George R. Prout has been designated as general manager. The new department will select and utilize appropriate marketing channels and methods for all of its products except air conditioning for rail transportation, which remains a responsibility of the transportation divisions of the company.

Bell Buildings to Expand. A substantial increase in the size of the plant of the Bell Telephone Laboratories will be made as soon as war restrictions permit. The buildings at Murray Hill, N. J., which accomodate more than 1,000 people, will be approximately doubled in size. The first unit of the suburban laboratory cost in the neighborhood of $2,500,000 and was opened in the autumn of 1941. Prominent among the new features are the quickly movable partitions and the ease with which wires, cables, and pipes may be installed or removed and yet concealed from view. Designed for peacetime use, the new laboratory was opened just as war was breaking. Here scores of war projects have been started, some small and completed quickly, others large and expanding from a room to whole sections of the building.

Television Program by Philco. The first television program ever broadcast from Washington, D. C., was transmitted recently to an audience in Philadelphia over a new multiple-relay television network developed by Philco Corporation, Philadelphia, Pa. Appearing on this inaugural telecast from Washington were Paul A. Porter, chairman of the Federal Communications Commission; Karl T. Compton (F '31), president of Massachusetts Institute of Technology, Cambridge, Mass., and chairman of the Research Board for National Security; and

John Ballantyne, president of Philco Corporation. In this new network, six television transmitters were used to carry the television pictures from the Philco studio in Washington to the final television station, WPTZ in Philadelphia. This multiple-relay television network was designed and built by Philco engineers.

Helping to Raise One Billion. Industrial firms of Manhattan Borough, New York, N. Y., intend to buy $1,000,000,000 in War Bonds during the Seventh War Loan. Among those who have volunteered to lead their respective units in the industry section are Theophilus F. Barton (F '30), commercial vice-president of the General Electric Company, New York, N. Y., and Henry C. Clement (M '13) assistant to the district manager, management department, of the same company. They are serving as chairman and cochairman, respectively, of the electrical unit.

New Name Adopted. For the sake of simplicity and brevity, the name of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been changed to Westinghouse Electric Corporation. The new name became effective on May 12, 1945.

EDUCATION . . . .

Fellowships at Ohio State University. Three fellowships in electron optics at The Ohio State University, Columbus, Ohio, have been provided by the Westinghouse Educational Foundation. One is a postdoctoral fellowship with a stipend of $3,000 per year and two are predoctoral fellowships with stipends of $1,000 per year. These are open to graduates in physics, mathematics, and electrical engineering.

Science Must Attract Students. "The increased demands for chemists, physicists, and others trained to carry on scientific research present a challenge to education. If such demands are to be met, students of superior ability must be sought out and attracted to the sciences." These remarks were contained in a recent report of Lee I. Smith, chief of the organic chemistry department of the University of Minnesota, Minneapolis, Minn., to the American Chemical Society. This report is a timely contribution to the postwar reorganization of the nation's 25,000 secondary schools.

Institute Celebrates Anniversary. Greetings from its namesake city in New Jersey to liberated Hoboken in Belgium, featured the Alumni Day celebration of the 75th anniversary of Stevens Institute of Technology on May 26. The letter was transmitted through the Belgian Information Center in New York.

Flying Boat in Service of Navy

This *PBM-5* (Patrol Bomber Martin) is the third model and sixth version of the twin-engine Glenn L. Martin "Mariner" series of flying boats. Powered by Pratt and Whitney *R*-2800 engines, the Mariners have redesigned engine cowlings, air scoops, and internal design changes. Jet-assisted take-offs also are employed in the *PBM-5*'s as they have been on earlier types. In combat action these *PBM*'s have ranged on search patrols within 100 miles of the Japanese mainland and on air-sea rescues have operated in waves from 8 to 12 feet high. During recent service-test hops at the Naval Air Station, Patuxent, Md., a *PBM-5* flew an endurance flight of 28 hours and 6 minutes

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

The Engineering Degree

To the Editor:

Professor Chester L. Dawes' letter concerning requirements for engineering degrees in the April 1945 issue of *Electrical Engineering*, prompts me to revive a suggestion which I have made many times in the 30 years just past, and which, so far, has met with universal disapproval.

I propose to abolish all degrees, engineering and others, thus ending automatically a futile and otherwise endless argument. Let us maintain our educational institutions with their faculties, libraries, laboratories, and other facilities; let any person attend, study what he likes for any convenient period, whether six months or six years; but let him take away nothing except what he has learned—no degree, diploma, or certificate. After all, it is the business of the school or college to advise and assist students in the acquisition of knowledge—not to classify and label them and to announce, by implication at least, that all yellow tags mark goods of the same quality.

The college would enjoy a number of incidental advantages. No one would matriculate except serious-minded persons, who really wanted to learn; the charlatan, in search of only a diploma which he might flaunt in the public eye, would have no place there. Extracurricular activities would be reduced to a minimum. The faculty would waste little time attempting to cultivate sterile ground. The number of students no doubt, would be smaller, but the useful output of the institution would be much greater.

In the past whenever I have suggested the abolition of degrees, someone invariably has popped up with the triumphant air of a cross-examining attorney about to spring a trap: "But, how is the personnel department of an employer to know whether a man is competent?" An equally pertinent question is: "How does it know anyway?" The answer to both questions is: "It doesn't." Anyone who has ever purchased an item from a mail-order house on the basis of a catalogue description will recall his disappointment when he found that the article was not what he wanted, although it conformed to the catalogue listing. The records of the personnel department are its mail order catalogue.

If the only purpose of a degree is to serve as a blanket letter of recommendation to employing agencies, it has come a long way on the down grade from its dignified and aristocratic origin.

If personnel departments have no better method of rating men than to accept at face value miscellaneous degrees from even more miscellaneous educational institutions, then it is high time that these departments should retire to that limbo of obscurity from which, only a few years ago, they emerged to plague

technical and operating departments by supplying misfit men chosen by artificial standards.

A personnel department would not have troubled itself to list the names of Alexander von Humboldt or Michael Faraday—they had no degrees. Likewise, Charles Darwin and Alfred Russel Wallace would have been out of luck. Even Isaac Newton and James Clerk Maxwell, with their trivial master of arts, would have been washed out by the flood of doctors of philosophy which threatens to submerge everything. We have been taught that Thomas A. Edison, Frank J. Sprague, and W. L. R. Emmet did important work, but perhaps that is an error—how could they without degrees?

Just what use does a man make of a degree? Does he write it when he signs his letters or checks? Does he insist on its use wherever his name appears in print, as, for example, in the telephone directory? There is one place where you are sure to find a full array of degrees, society memberships, and other more or less significant details of the author's real or fancied importance—that is on the title page of a book. This, however, must be taken as what is called in the law a "self-serving statement." I always have suspected that its principal purpose was to dazzle the reader, so that he might not discover that everything in the book had been printed many times before.

The United States of America was founded on the alleged belief that "all men are created equal." It seems likely that every man who affixed his signature to that declaration did so with his tongue in his cheek; but, however sincere the signers may have been, every one of their heirs, successors, and assigns has struggled ever since to obtain some kind of designation to indicate *his* superiority to the common herd of "equals." It is an amusing phenomenon—this frantic scramble for titles of distinction among a people who have shouted longer and louder and to less effect than any others about the equality of all men.

There are men who study because they enjoy it, because they find pleasure in contemplating the phenomena of the universe and in the effort to correlate their observations. To such persons a degree means less than nothing. As to those who expect to utilize their educations (?) in a competitive field, let them be sporting enough to enter in open contest with all comers without demanding a handicap and to prove their claimed superiority by the results of their work.

Today many department stores require that members of their sales force shall hold academic degrees, and some so-called "advanced" Boards of Education insist that a doctorate is the indispensable qualification for teaching in a grade school. The whole matter of degrees has become ridiculous. The electrical engineer should hold them in contempt.

CHARLES W. COMSTOCK (M '38)

(Consulting engineer, Jackson Heights, N. Y.)

NEW BOOKS

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

High-Frequency Induction Heating. By F. W. Curtis. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1944. 235 pages, illustrated, 8½ by 5¼ inches, cloth, $2.75. (ESL.)

The industrial applications of induction heating are explained. Heating procedures and principles and the constructional features of industrial heating coils are described in detail, and fixture design and process handling equipment are outlined broadly. The book is intended to simplify the application of induction heating and to assist in the installation of equipment for specific operations.

Partial Differential Equations of Mathematical Physics. By H. Bateman. Dover Publications, New York, N. Y., 1944. 522 pages, illustrated, 9½ by 6 inches, fabrikoid, $3.95. (ESL.)

Methods are presented for solving boundary-value problems of mathematical physics by means of definite analytical expressions. The work is restricted to partial differential equations, with only brief mention of the Heaviside calculus and the theory of integral equations. The book contains a wide range of representative problems and nearly 1,200 references to classical and contemporary literature. It is intended as both a text and reference work for mathematicians and physicists and aeronautical, electrical, and mechanical engineers.

Aircraft Vibration and Flutter. By C. R. Freberg and E. N. Kemler. John Wiley and Sons, Inc., New York, N. Y.; Chapman and Hall, London, England, 1944. 214 pages, illustrated, 8½ by 5½ inches, cloth, $3. (ESL.)

In nontechnical language, with a minimum of mathematics, this book explains the fundamentals and general phases of vibration and flutter affecting both stationary-wing and rotating-wing aircraft. The material is arranged to give practical aid in problems of aircraft testing and analysis. Engine isolation and soundproofing are dealt with in an early chapter. There is a bibliography.

Commercial Waxes. A symposium and compilation edited by H. Bennett. Chemical Publishing Company, Brooklyn, N. Y., 1944. 583 pages, illustrated, 8¾ by 5½ inches, cloth, $11. (ESL.)

All classes of waxes, such as mineral, vegetable, animal, insect, synthetic, and compounded waxes are discussed in detail. Full particulars are given concerning physical properties, sources, and uses. Wax technology and the handling and compounding of waxes are described. A glossary is included, and an extensive section gives formulas of commercial materials containing waxes, such as adhesives, construction materials, coatings, soap, and cleaners.

Modern Synthetic Rubbers. By H. Barron. Second edition revised and enlarged. D. Van Nostrand Company, Inc., New York, N. Y., 1944. 355 pages, illustrated, 8¾ by 5½ inches, cloth, $6.50. (ESL.)

The primary purpose of this book, which appeared in 1942, was to awaken Great Britain to the growing importance of synthetic rubber. It presented a systematic account of the new material, considered historically, scientifically, and technically, as revealed in the literature. The present edition has been revised thoroughly to take account of developments since 1942, especially those resulting from work in the United States.

English-Spanish and Spanish-English Dictionary of Aviation Terms. By J. K. Serralles. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1944. 131 pages, 7½ by 5 inches, fabrikoid, $2.50. (ESL.)

Aviation terms used in Spanish America differ considerably from those used in Spain, as more terms have been adopted from the English language. The present work is based on usage in South America.

The Industrial Housekeeping Manual. By R. F. Vincent. National Foremen's Institute, Inc., Deep River, Conn., 1945. 116 pages, 5½ by 8 inches, cloth, $2.50.

A guide—methods, schedules, and organization—in establishing an adequate housekeeping and sanitary work program is addressed to building managers, supervisors, and cleaning crew foremen.

PAMPHLETS

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Magnetic Wire Sound Recorder and Reproducer. Armour Research Foundation of Illinois Institute of Technology, Chicago 16, Ill. Press Book 1, 53 pages.

Research, Invention, and Patents. By Andrey A. Potter. Industrial Research Institute, New York 17, N. Y., 8 pages.

Lighting Drafting Rooms. *Architexts*, April 1945. Holophane Company, Inc., New York, N. Y.

Republic Silicon Steels, Technical bulletin. Republic Steel Corporation, Cleveland 1, Ohio.

Permanent Magnets. Raymond L. Sanford. United States Department of Commerce, Washington, D. C., 39 pages.

Lear Know-How. Lear, Inc., Piqua, Ohio, 22 pages.

Radio and Electronic Equipment. Walker-Jimieson, Inc., Chicago 12, Ill., 35 pages.

Wheelco Electronic Controls. Wheelco Instruments Company, Chicago, Ill., 12 pages.

Fiberglas. Owens-Corning Fiberglas Corporation, Toledo, Ohio, 8 pages.

Vari-Typer (a new tool for business). Ralph C. Coxhead Corporation, New York 14, N. Y., 16 pages.

Selenium Rectifiers. Fansteel Metallurgical Corporation, North Chicago, Ill., 12 pages.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Modern Electric-Power-Distribution Ideas as Applied in a Large War Plant

R. H. KAUFMANN
MEMBER AIEE

N. A. KIEB
MEMBER AIEE

IT now becomes possible to reveal the composition of a typical war-plant electric distribution system (aircraft-engine manufacture). It is the hope of the authors that many of the principles and practices which have been embodied in this electric system can be adopted by others to effect the simplification and economies in power distribution that have been done in this instance.

In December 1941 this nation was plunged into the present world conflict. Participation was no longer optional. In this, a mechanized war, there arose an immediate demand for almost every conceivable type of machine for use on land, on the sea, and in the air in unheard of quantities. It became essential that every man-hour of effort and every pound of material be made to yield the greatest return.

The direct objectives considered foremost in the creation of the electric system herein described included:

1. Speedy completion.
2. High utilization efficiency of material, particularly copper and steel.
3. Conservation of man-hours in manufacture, installation, and operation.
4. An electric system as nearly independent of building structure as possible.
5. The incorporation of an acceptable degree of electrical service reliability.
6. Assured safety to equipment and personnel.

In the interest of speeding the work and securing the maximum degree of coordination and economic balance, the entire electric distribution system was negotiated as a single project. The cooperative efforts of the Pratt and Whitney Aircraft Corporation; Albert Kahn, Architects and Engineers; the General Electric Company; together with the Defense Plant Corporation, were enlisted to that end. Paul R. Olson of the East Hartford Pratt and Whitney organization deserves particular credit for his untiring efforts in expediting this project.

Paper 45-79, recommended by the AIEE committee on industrial power applications for presentation at the AIEE winter technical meeting, New York, N. Y., January 29-26, 1945. Manuscript submitted November 27, 1944; made available for printing January 2, 1945.

R. H. KAUFMANN is in the industrial engineering department of the General Electric Company, Schenectady, N. Y., and N. A. KIEB is electrical engineer with the Pratt and Whitney Aircraft Corporation of Missouri, Kansas City, Mo.

The Electric Distribution System

A bird's-eye view of the complete distribution system is presented by the overall one-line diagram, Figure 1. The several component parts as portrayed in this diagram represent the approximate geographical arrangement.

In immediate evidence is the application of the load-center principle of power distribution which has been publicized quite widely: "Transmit power at the highest practical voltage to relatively small distributed substations". In this instance, primary distribution is accomplished at 13.8 kv.

Reliability of electric service is incorporated in the form of the secondary selective arrangement in which each individual load circuit has access to an alternate independent source of low-voltage power. This system has met its expectations with flying colors, possessing the following outstanding advantages:

1. Both normal and emergency operation incorporate the simplicity of radial distribution
2. All circuit equipment normally shares in carrying the total load resulting in low power and reactive kilovolt-ampere loss, as well as better maintained delivered voltages.
3. Emergency operation entails merely the opening of the low-voltage circuit breaker in the de-energized source and closing the tie breaker.

It will be observed that effective duplication of electric service is carried through to the incoming 110-kv supply system. The two co-ordinating primary feeders at each and every substation originate from different 13.8-kv busses. Both of the latter in turn may be energized by either or both main transformers and, should a second 115-kv feeder be added, from either or both incoming high-voltage lines.

In the belief that the most logical presentation will parallel the sequence followed in initial planning, the several specific load areas will be described first and be followed by a description of the primary-feeder arrangement and main incoming-power substation.

Main Factory Building

The main factory building encloses under a single roof a ground area of 1,000 feet by 2,000 feet. Operations are conducted on a single floor at ground level, with the exception of a mezzanine floor over about ten per cent of the area, making a total working floor space of about 2,250,000 square feet. Of this total area, approximately 70 per cent is devoted to active manufacture; 15 per cent to rough stores; ten per cent to finished parts receiving, assembly, and shipping; and five per cent to inspection. The mezzanine floor is allocated to inspection and a portion of the active manufacture.

Supplying general-purpose power and light to this area are 16 load-center unit substations aggregating 30,000 kva, representing about 13.3 volt-amperes per square foot of working floor space. In one load area, an additional load-center substation has been installed because of a high concentration of power in the form of heat-treating equipment. In general, the area served by a single substation is about 250 feet by 500 feet, but is somewhat larger in areas characterized by lower power-utilization densities. In the rough-stores area the supply substation capacity is reduced by the application of 750-kva transformer units, in contrast with 1,000-kva units used elsewhere.

The substations are installed in enclosures forming a part of ventilating-fan houses located on the building roof. The reasons for this selection are: 13.8-kv feeder cables are supported on racks close to the building roof; the bulk of the power is distributed to plug-in bus also located closer to the roof than to the floor; and the fact that the enclosures could be integrated with houses there located for other purposes.

Equipment was hoisted through a large hatchway later closed with a removable wood cover. Each substation was handled in three pieces (the two Pyranol-filled transformers and the switchgear section) using a portable A frame above the hatchway. The A frame has been retained for possible future use. The installation procedure was carried

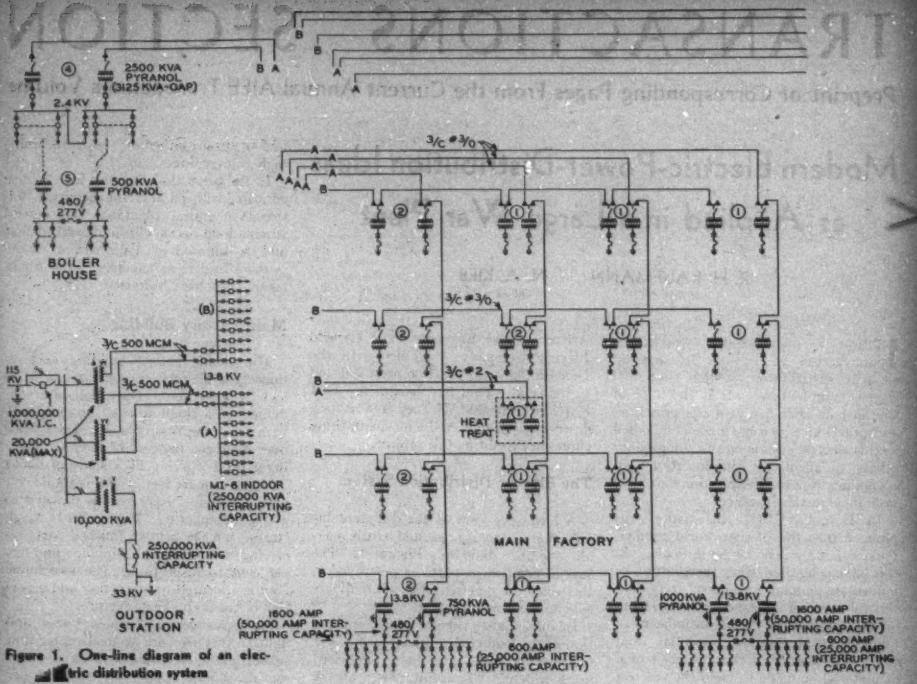

Figure 1. One-line diagram of an electric distribution system

out without difficulty or incident.

A photograph of an installed substation is reproduced in Figure 2. The electrical composition is portrayed by the one-line diagram, Figure 1. The high-voltage magnetizing-current switch on each transformer is key interlocked with the low-voltage main circuit breaker. Key interlocking is included to permit closure of the low-voltage tie circuit breaker only when one of the transformer secondary circuit breakers is open.

Both power and light are served by common load-center unit substations using a 460—265 four-wire grounded-neutral system to supply 440-volt polyphase motors in the normal manner and 265-volt fluorescent lighting units from line to neutral potential. Plug-in bus is used to distribute power to the major portion of the load, consisting of distributed machine tools, so as to obtain the flexibility needed to accept fairly frequent rearrangement of machine tools for production efficiency, improvement, or changed requirements.

Factory Power Distribution

The manner in which low-voltage power is distributed from the load-center unit substations to the plug-in bus sections for a typical unit load area is illustrated in Figure 3. Two adjacent 230-foot lengths of 250-ampere War Production Board approved plug-in bus are fed from their center point by an individual power feeder from the substation. To avoid operation at undue temperature on the plug-in bus, should the load be badly disproportioned among the four radial extensions, a temperature alarm (including bell and lamp) is installed adjacent to the feeder tap on each bus section which will sound an alarm upon reaching an 80-degree centigrade operating temperature. A typical feeder tap to a plug-in bus section is illustrated in Figure 4. Each power feeder consists of three single-line conductors plus one bare neutral conductor, which conductors are spaced symmetrically by means of trisected porcelain support blocks. Individual conductors are kept taut by straining them in the horizontal direction to structural members of the building. The manner in which this is accomplished will be evident by inspection of Figures 4 and 8.

Factory Lighting Distribution

Fluorescent lighting was adopted in the interest of economy. On first thought, the copper and steel in fluorescent ballasts might indicate that incandescent lighting would have the advantage. But the greater light efficiency of fluorescent lamps reduces the power requirement of the factory area by some 6,000 to 7,000 kw. The copper and steel which would be required in the complete electric system from prime mover to lamp to supply this additional load would exceed the copper and steel needed in the fluorescent-lamp ballasts. The material requirement

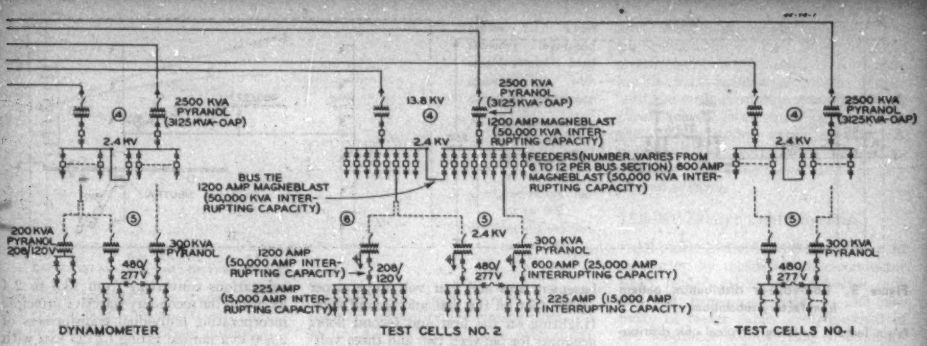
2500 KVA PYRANOL (3125 KVA-OAP)
2.4 KV
13.8 KV
2500 KVA PYRANOL (3125 KVA-OAP)
1200 AMP MAGNEBLAST (50,000 KVA INTERRUPTING CAPACITY)
2500 KVA PYRANOL (3125 KVA-OAP)
2.4 KV
FEEDERS (NUMBER VARIES FROM 6 TO 12 PER BUS SECTION) 800 AMP MAGNEBLAST (50,000 KVA INTERRUPTING CAPACITY)
2.4 KV
BUS TIE 1200 AMP MAGNEBLAST (50,000 KVA INTERRUPTING CAPACITY)
200 KVA PYRANOL 208/120V
300 KVA PYRANOL
480/277V
1200 AMP (50,000 AMP INTERRUPTING CAPACITY)
208/120V
225 AMP (15,000 AMP INTERRUPTING CAPACITY)
2.4 KV
300 KVA PYRANOL
480/277V
600 AMP (25,000 AMP INTERRUPTING CAPACITY)
225 AMP (15,000 AMP INTERRUPTING CAPACITY)
300 KVA PYRANOL
480/277V
DYNAMOMETER
TEST CELLS NO. 2
TEST CELLS NO. 1

Figure 1 (continued)

of the 265-volt design are much less than for the 120- or 208-volt design. Also the supply of both light and power from common load-center unit substations results in further economy of materials. An ingenious innovation is represented by the suspension of a series of fluorescent units from an overhead messenger cable. A single number-12 conductor, in combination with the messenger as a ground return, serves a four-kilowatt lighting load.

A sketch showing the fundamental aspects of factory lighting distribution is included in Figure 3. Ten 400-watt fluorescent fixtures are supported from one overhead horizontal messenger cable. Each fluorescent fixture taps the number 12 feeder line carried horizontally directly below the messenger through the fuse. Three such adjacent strings of fluorescent lights are fed from a three-phase tap from the main lighting feeder through circuit breakers located in a building column five feet above floor level.

The resulting lighting in this plant is excellent. The relatively low intrinsic brilliance of fluorescent lamps, together with their location about 16 feet above floor level, produces the effect of a ceiling of soft light and almost complete absence of shadow. It has been observed that this ceiling of light tends to obscure equipment mounted above that level and effectively hides the maze of pipes, cableways, vertical suspension members, and the like, which had been expected would constitute an eyesore. Experience to date indicates that an average fluorescent lamp life in excess of 7,000 hours is being obtained.

To supply a relatively small amount of 120-volt power to column receptacles for miscellaneous hand tools, portable lights, and so forth, and for lighting and receptacle power in basement washrooms, small air-cooled transformers are distributed over the factory area, taking single-phase power from the 480-volt system and converting it to 240–120 volt. This power is distributed by branch circuits of relatively short length.

Capacitor Application

About 10,000-kva in capacitors have been applied to the 480-volt distribution system, in 90-kva blocks directly adjacent to the feeder tap in the plug-in bus. The principal reason for the capacitive kilovolt-amperes is a power-contract power-factor clause limiting the power factor to not less than 0.975 lagging. By absorbing the reactive kilovolt-amperes near its origin (machine-tool load), the reactive kilovolt-amperes and power loss which would be incurred by transmission through the distribution system is avoided.

Capacitor application constitutes an extremely flexible means of enhancing the load-carrying ability of a particular load-center unit substation. Figure 5 defines the increase in load which may be accepted in combination with a particular amount of capacitor kilovolt-amperes, for a basic load power factor of 0.6 and 0.8 lagging. With a load power factor of 0.6 lagging (typical of machine-tool load), it will be observed that the amount of such load which can be accepted by a 1,000-kva substation without exceeding its rating can be increased to 1,300 kva by the application of 420 kva in capacitors. *Thus an excess machine-tool load of 300 kva could be accepted, as needed at an investment cost of $11 per kilovolt-ampere (420 kva of capacitors at $8 per kilovolt-ampere installed), which is no greater than the cost of increased capacity in the basic power-distribution system.*

Grounding System

Considerable study was given to the attainment of an adequate grounding system, which assumes particular significance in reinforced-concrete building construction. The unintentional transfer of ground current between various metallic members or structures is to be avoided. It is particularly important that there exist a positive direct path to the supply transformer neutral to conduct ground-fault current during the existence of a circuit ground fault to avoid sputtering or arcing between metallic members which may be in light contact and to avoid differences of potential between exposed metallic bodies, which might constitute a hazard to personnel.

Beneath each substation are driven four $^3/_4$-inch diameter, ten-foot-long Copperweld ground rods interconnected with the associated substation neutral bus. At each station these are bonded to heavy water mains, which in general traverse the plant in the north–south direction. Between adjacent unit load areas in the east–west direction, the 4/0 neutral cable of the outermost power feeder is continued and joined to the corresponding neutral in the next adjacent load area, and the lighting messenger cables are interconnected electrically from one load

Figure 2. Typical 2,000-kva 13,800- to - 480–277 - volt secondary selective factory load-center unit substation

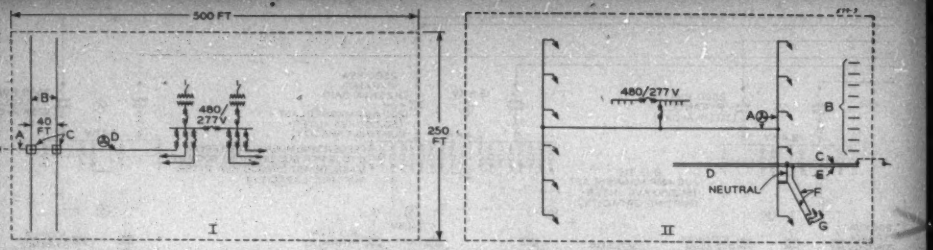

Figure 3. Low-voltage distribution pattern from factory substations

Main factory building: typical unit distribution

I. Typical power-distribution feeder
A—4/0 neutral to next area
B—250-ampere plug-in bus
C—Power-factor capacitors applied
D—Three 350,000-circular-mil conductors, one 4/0 neutral

II. Typical lighting-distribution feeder
A—Three number-four conductors, one number-six neutral
B—Messengers spaced approximately 15 feet
C—Steel messengers
D—Ten 400-watt fluorescent units suspended from this messenger
E—Number-12 copper
F—Three number-12 in conduit
G—Column switches at floor level

area to the next. This entire grounding system is interconnected with the main substation grounding system by way of the main water-piping system and the metallic sheaths of the multiplicity of power feeder cables.

Office Building

The office building covers an area of 80 feet by 2,000 feet and is in contact with the long dimension of the main factory building. This portion of the structure incorporates a basement, a first, and a second floor. The basement, devoted to storage and a small amount of miscellaneous machinery and with fairly low illumination levels, represents an area of low electric-load density. The first and second floors are devoted to active office service, including normal illumination intensities, column-mounted fans, and the usual array for electrically operated business machines.

This load area is served by four load-center unit substations of secondary selective design, functionally equivalent to those located in the factory, differing in that the low-voltage service is 208–120 volt and individual Pyranol transformers are rated 200 kva. The aggregate substation capacity of 1,600 kva can accommodate an electric-load density of two volt-amperes per square foot in the basement area and four volt-amperes per square foot on the first and second floor. (Lighting on the first and second floors accounts for between two and three volt-amperes per square foot.)

These substations are located in houses (wood construction) on the factory roof directly adjacent to the office building. An illustration of one installation appears in Figure 6. The low-voltage feeders from each substation drop through the factory roof and then are carried horizontally, and the same type of construction is used as for factory feeders. At appropriate points, branch circuits are carried through the wall to the office building and dropped vertically in conduit to supply distribution cabinets at the second, first, and basement floor levels. The detail arrangement of this low-voltage feeder system is portrayed schematically by the sketch, Figure 7. A section of the horizontal feeder array beneath the factory roof adjacent to the office building is shown in Figure 8.

From the wall distribution cabinets, conventional distribution practice is followed using conduit for permanent installation, such as lighting fixtures and Walker underfloor duct for flexible installation of business machine and other electrical outlets.

Engine Test and Dynamometer Area

This section of the plant is devoted to production and experimental engine testing and occupies an area of 250 by 900 feet. Each production test cell requires a 250-horsepower blower motor together with several small motors, driving fans and pumps, and special interior lighting of explosion-proof character. There are associated areas requiring illumination equivalent to that provided in the factory area with relatively low power load density. That portion devoted to experimental engine test involves electric power requirements similar to those of the production test area but in addition incorporates electrical-test dynamometer equipment of which the present equipment utilizes two 1,250-kva and one 750-kva synchronous rotating machines. There are also a number of motors of 300- and 600-horsepower rating.

Serving this load area are three unit substations converting from 13.8 to 2.4 kv, using the secondary selective principle incorporating individual transformers of 2,500-kva normal rating (3,125 kva with supplementary cooling) in combination with metal-clad vertical-lift switchgear sections utilizing Magne-blast circuit breakers of 50,000-kva interrupting capacity. The two complementary sections of the substation are installed face to face, as illustrated in Figure 9. The tie breaker is installed in one lineup, and the bus from the other section is extended by means of 500,000-circular-mil three-conductor five-kilovolt cable.

The stator circuit of each 2,300-volt machine is connected directly with its respective switching position in the metal-clad lineup by means of three-conductor five-kilovolt cable. In general, the normal control of each motor circuit breaker is from a control panel adjacent to the controlled machine. Figure 10 shows a group of synchronous-motor field cubicles on each of which is mounted the control switch which actuates the circuit breaker in the metal-clad structure. The metal-clad circuit-breaker position contains a permissive control switch, which allows

Figure 4. Typical construction employed for factory 480–277-volt feeders

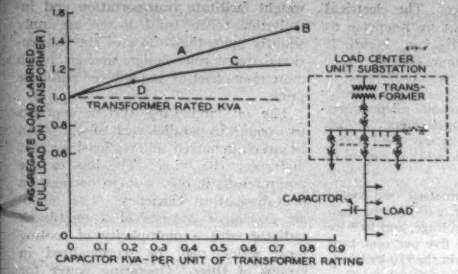

Figure 5. Chart showing increased machine-tool load permissible with capacitor assistance

A—Load power factor = 0.6
B—Net power factor = 0.9
C—Load power factor = 0.8
D—Net power factor = 0.9

the circuit breaker to be tripped locally and can be positioned to prevent closing the breaker from the remote station.

Small motors and general-purpose lighting are served by load-center unit substations supplying 460–265-volt service, which closely resemble those employed in the factory area, except that they are of smaller rating and are served at 2.4-kv from the main stations. A typical unit is illustrated in Figure 11. For the special test-cell lighting and some other miscellaneous load demanding 120-volt service, there are provided small load-center unit substations delivering 208–120-volt service. A consideration of these several auxiliary load-center unit substations as to unit capacity, switching, and protection requirement, indicated that they could be served more economically at 2.4 kv through the larger substations than directly at 13.8 kv.

Boilerhouse Area

The electric-load demands in the boilerhouse closely resemble those of the engine-test and dynamometer area. A substantial number of motors with ratings in excess of 100 horsepower are employed for powering cooling-tower fans, air compressors, water-circulating pumps, and fire pumps which were most effectively served at 2.4 kv. In addition, there exists the usual array of boilerhouse small auxiliaries in the form of fans, blowers, and pumps, which are best adapted to low-voltage service.

Serving this load is one secondary selective substation converting from 13.8 kv to 2.4 kv with component parts duplicating those employed in the test-area substations. Considerations of floor area made an end-to-end installation arrangement preferable, as illustrated in Figure 12. Low-voltage power is supplied by a load-center unit substation delivering 460–265-volt service in the same manner as was done in the test area.

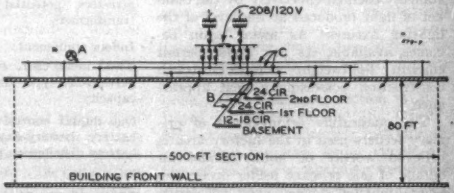

Figure 7. Low-voltage distribution pattern from office substations

Typical unit distribution for office building

A—Three 4/0 conductors; one 1/0 neutral
B—To each floor: three number four, one number-six neutral in conduit
C—Strained horizontally along office wall in the factory area

The electrical demands in the boilerhouse area are at their maximum level during the summer months, when the refrigerating plant assumes its maximum demand. During that season the substation is loaded to its rated capacity.

To insure the maintenance of an adequate ground system for the boilerhouse area, which is physically set apart from the remainder of the plant building, ground cables are installed interconnecting the local boilerhouse ground system with the main substation ground network paralleling the interconnection formed by the 13.8-kv-feeder cable sheaths. A multiplicity of water pipes also interconnects the boilerhouse and factory ground systems.

13.8-Kv Feeder Cable System

All power is distributed from the main substation by means of three-conductor 15-kv leaded cables with asbestos tape and red flameproof paint. The majority of feeder cables are composed of 3/0 conductor, representing an economical balance between copper and sheath-metal requirements. Several cables employ a number 2 conductor, which represents about the smallest size which can be employed safely with a 250,000-kva short-circuit level at the source end. Instantaneous attachments on these feeder-cable protective relays are applied and required to avoid the attainment of damaging copper temperature due to primary-circuit fault-current flow.

Except for circuits leading to the boiler house, the 13.8-kv cables are supported on wood lattice* racks or troughs suspended from the building roof above the level of the illumination fixtures. This method of handling cable runs possesses many admirable qualities, which can be used advantageously in future applications. Practically no advance preparation of building structure is needed. Cables are easily pulled into place. In the present instance, full reel lengths of 1,000 feet were pulled into place without the slightest difficulty. To assist in pulling around corners, a jig was prepared which forms a 24-inch radius arc, around the periphery of which a number of wood rollers were arranged. By temporarily clamping this jig at a corner, the cable was swung around a 90-degree turn with a very small amount of drag. Splices can be made at any spot along the trough. Cables are cut only when a point of termination is reached. The entire length of cable is accessible after installation. Repairs can be made with no

Figure 6. Typical 400-kva 13,800-to-208–120-volt secondary selective office load-center unit substation

* It is recognized that this does not comply with the National Electrical Safety Code requirements, but it is applicable as a method of meeting wartime conditions.

Figure 8. Typical view of office main 208–120-volt feeders showing branch-circuit tap

waste of cable and without disturbing any section of the cable other than a damaged portion. Permissible current load levels are no less and may be greater than those permitted in underground runs. Typical views of the installed cable way are included in Figures 4 and 8. Though the appearance of the cable trench itself is not particularly pleasant, it is, as installed, obscured effectively by the blanket of light produced at the level of the lighting fixtures. As metal again becomes available, its use would permit efficient lightweight compact trough construction possessing a neat appearance.

The quadrature arrangement of primary feeders used in the factory area is believed worthy of note. Should an outage of one primary feeder occur, the several affected stations each will derive its emergency load from different primary feeders. Thus the emergency load resulting from the loss of one primary feeder is distributed among four other feeders. It also will be evident that the two feeder cables, to any one substation, traverse entirely different routes and thus are unlikely to be disrupted simultaneously.

Main Incoming-Power Substations

The incoming-power substation accepts power at 110 kv, converts to and distributes at 13.8 kv, to the various unit substations previously described. Provision also is included for interconnection with 33-kv service. The electrical features will be evident by reference to the over-all one-line diagram, Figure 1. Principal equipment items include:

Outdoor equipment:

Two 20,000-kva forced-oil air-pressure-cooled three-phase transformers, 110-kv delta high voltage, 13.8-kv wye low voltage, with four $2^1/_2$ per cent taps below normal in the 110-kv winding.

One 10,000-kva oil-immersed self-cooled three-phase transformer, 110-kv wye high voltage 33-kv wye low voltage, and 13.8-kv delta tertiary with two five per cent taps above and below normal in the 110-kv winding.

One 115-kv oil circuit breaker with isolating and by-pass disconnect switches.

One 33-kv oil circuit breaker with isolating and by-pass disconnect switches.

Three 115-kv transformers, high-voltage disconnect switches, horn gap.

One substation structure, wood construction.

Grounding resistor for the 13.8-kv system.

Auxiliary equipment including lightning arresters, potential devices and current transformers.

Indoor equipment:

Two metal-clad switchgear assemblies, vertical-lift type, 250,000-kva interrupting capacity.

One duplex control board, control power battery, battery-charging equipment, and battery distribution panel.

Main 20,000-Kva Transformers

Forced-oil air-pressure cooling of the main 20,000-kva transformers was adopted primarily as a material conservation means. Subsequent experience indicates that it merits extensive use at attended stations. The smaller size and lighter weight facilitate transportation and installation. The total losses are only slightly more than those of the conventional transformer design, and are much more than offset by the reduced purchase price.

The oil circulating system contains two pumps in parallel, each of which can be cut off, removed, and replaced without disturbing the other. The loss of one pump results in only a slight decrease in heat-dissipating efficiency. The oil-to-air exchanger consists of a multibank radiator with a multiplicity of cooling fans, which may be sectionalized in groups of three. Operating power for fans and pumps is derived from control power transformers included in the indoor metal-clad structure.

The split 13.8-kv winding design as employed in the main transformers accomplishes the following:

1. Each transformer serves as a source to two bus sections, permitting continued operation of both busses with one transformer out of service; without the aid of external reactors or bus-tie circuit breakers.
2. Short-circuit interrupting requirements are controlled by inherent transformer reactance. The internal winding configuration is such as to make the external characteristics equivalent to two independent 10,000-kva units.
3. All circuit breakers are of identical rating (600 amperes).
4. A change in voltage ratio of the main power transformers is accomplished easily without de-energizing either bus section. One transformer may be de-energized, its ratio changed by one tap, and then restored to the system, following which the same procedure would be repeated on the second transformer. The temporary circulating current in the transition stage will be limited to a small fraction of rated value.

The neutrals of both 13.8-kv winding sections are interconnected and brought out to permit grounding. The high-voltage winding is connected in delta to stabilize magnetically the three-phase transformer and also to make the grounding systems of the 13.8-kv and the 110-kv system independent. Each transformer 13.8-kv neutral is grounded through an outdoor-service grounding resistor, limiting the ground fault current to a low

Figure 9 (left). View of typical 5,000-kva 13.8- to 2.4-kv secondary selective test-area unit substation with the two sections mounted face to face

Figure 10 (right). A group of typical synchronous-motor field cubicles from which motor control is effected

Figure 11. View of typical 600-kva 2,400 to-480–277-volt secondary selective load-center unit-substation

value, (not exceeding 1,000 amperes). Grounding of the 13.8-kv neutral in this manner maintains the system voltage normally symmetrical with respect to ground, provides a source of ground current for fast ground-fault relaying, minimizes transient-voltage surges resulting from switching operations, and is free from excessive overvoltages of repetitive restrike origin.

Auxiliary 10,000-Kva Transformer

The size and design of the 10,000-kva auxiliary transformer was worked out in conjunction with the affiliated power utility company. The 110-kv and 33-kv windings are connected in wye to provide means of grounding these neutrals and to establish zero-phase shift between the 110- and 33-kv terminal voltages. A necessary tertiary winding was wound for 13.8 kv and connected so that the resulting terminal voltage agrees in phase with that derived from the main transformers.

The function of this transformer is threefold:

1. To supply 13.8-kv power on a temporary basis from the 33-kv system for initial plant operation (3,500 kva maximum).

2. To serve permanently as a means of securing emergency power, in limited amounts, from the 33-kv system should the 110-kv supply be interrupted.

3. To provide means of transferring power from the 110-kv to the 33-kv system.

Prior to the availability of 110-kv power, this transformer served a number of unit substations in a temporary toolshop area, enabling the manufacture of tools and jigs to be initiated. About 400,000 square feet of working area was being served in this manner at the time primary power became available, although power-load levels were subnormal as would be expected (about 1,000-kva power load and approximately 400-kva lighting load).

Grounding System

The grounding system at this station involves a multiplicity of driven Copperweld ground rods distributed over the outdoor substation site. The installation of an inverted tile, flush with the ground surface and equipped with a wood cover at each ground rod, serves to keep the ground-rod terminal clamps out of contact with the earth, thus minimizing corrosion, and makes each connection accessible for inspection or measurement of resistance. Ground cables are installed leading to the indoor station, paralleling the incoming 13.8-kv power cable sheaths and integrating the grounding system of the entire plant.

Indoor Station

The indoor station, located along the factory end wall, includes two sections of 15-kv vertical-lift metal-clad switchgear (250,000-kva interrupting capacity), through which the 13.8-kv power is directed to plant feeders. Between these two sections is located a duplex board at which the primary control of the station is affected.

The front of the duplex board is devoted to the control of the 110-kv, 33-kv, and 13.8-kv transformer circuits; primary station metering and indicating instruments; and the master annunciator; arranged as shown in Figure 13. The rear of the duplex board is devoted to relays associated with incoming-power circuit protection up to the 13.8-kv metal-clad busses; and switching equipment for the station a-c auxiliary power, the appearance of which is illustrated in Figure 14.

Both sections of the metal-clad switchgear are assembled to be symmetrical with respect to the central duplex board. Incoming-power circuits are adjacent to the duplex board, and feeders for the various services appear in successive order. One switchgear section is illustrated in Figures 15 and 16. Circuit-breaker controls, indicating instruments, and relays for each feeder circuit are located on the corresponding metal-clad unit, although the opening of any feeder breaker will be announced and identified by an annunciator drop at the duplex board.

Outgoing feeder cables leaving the metal-clad structure are racked in a cable trench with a removable cover (see Figure 16), from which they pass through the adjoining wall into the factory build-

Figure 12. View of 5,000-kva 13.8- to 2.4-kv boilerhouse unit substation with the two sections mounted end to end

Figure 13. Front view of main substation duplex control board

Figure 14. Rear view of main substation duplex control board

Figure 15 (left). Front view of one section of the 13.8-kv main substation vertical-lift metal-clad switchgear

Figure 16 (right). Rear view of metal-clad switchgear section shown in Figure 15

ing. They then are run up to the overhead cable troughs as illustrated in Figure 17.

Auxiliary a-c control power for main-transformer auxiliaries, indoor and outdoor station lighting, and control-battery charging is supplied by one 25-kva transformer, with a 208–120-volt low-voltage winding, incorporated in one unit of each metal-clad assembly. The auxiliary load normally is proportioned between the two units, but provision is made for switching the total load to either transformer in an emergency. Essential station lights are equipped with an automatic transfer relay, by which they are energized from the control battery, should the normal source fail. The emergency lighting circuit is fused separately at the battery distribution panel. The control battery, associated charging equipment, and distribution panel are installed in an adjacent room.

Interlocking

The electrically operated high-voltage horn-gap disconnect switches associated with the 20,000-kva transformers are interlocked electrically, with their respective low-voltage circuit breakers permitting them to be opened only when both low-voltage circuit breakers are open. The manually operated ratio-adjuster switches on these transformers also are interlocked to permit operation only when both the high-voltage disconnect switch and the two low-voltage circuit breakers are open. An inherent feature of vertical-lift metal-clad switchgear is an interlock, which prevents the circuit breaker from being moved to the disconnect position with the circuit-breaker element closed.

Relaying

All 13.8-kv feeder units are equipped individually with inverse-time overcurrent line and ground trip relays, the former co-ordinated to be selective with unit substation switching equipment. Instantaneous attachments, set above the current level obtained with a unit substation low-voltage bus fault, also are applied to avoid damaging internal temperature on the number-2-conductor feeder cables by shortening the clearing time in the presence of high fault-current magnitudes.

The 13.8-kv incoming-power circuits are equipped individually with inverse-time overcurrent line and ground relays co-ordinated to be selective with feeder-circuit line- and ground-relay protection.

Transformer differential-relay protection is applied to each of the 20,000-kva and the auxiliary 10,000-kva transformers. While the absence of individual high-voltage circuit breakers requires that the entire system be de-energized, the differential protective relays minimize internal damage by promptly interrupting the source of power, and, by relay targets, identifies the unit in trouble, enabling it to be isolated immediately and service restored promptly on remaining equipment.

The 110-kv incoming-line circuit is provided with inverse-time overcurrent line and ground relays, the former selectively co-ordinated with 13.8-kv switching equipment and the latter co-ordinated with ground relaying at the source end of the line. Power directional relays directed outward are applied to obtain automatic opening of the 110-kv oil circuit breaker as a result of external trouble on the 110-kv line.

The 33-kv incoming-line circuit is equipped with inverse-time overcurrent line and ground relays, together with power directional relays, selectively co-ordinated with remotely located 33-kv protective equipment.

A few words might be devoted appropriately to an explanation of how the 13.8-kv neutral grounding improves the fault protective picture. The 13.8-kv ground-relaying system involves only those circuit elements intervening between the transformer low-voltage neutral and the terminals of the 13.8-kv feeders. All circuit faults within this zone involving ground can be isolated correctly more rapidly, and with a greater margin of selectivity. Except for transitory surges of very short duration, no ground current flows in healthy feeder circuits. Feeder ground relays may be made sensitive and fast. Circuit faults involving only ground during the clearing interval will be subjected to only the limited ground fault current, thus further limiting the energy liberated at the fault. In the system here used, the flow of ground fault current in the 13.8-kv system does not result in ground current flow in circuits operating at other voltages. Neither will ground current flow elsewhere cause current flow in the 13.8-kv ground-relaying system.

Metering

The main substation incorporates the following instrument and metering equipment:

Ammeter in the 110-kv incoming line.

Ammeter in the 33-kv line circuit.

Voltmeter for each 13.8-kv bus.

Ammeter in each 13.8-kv incoming line.

Wattmeter for each 13.8-kv bus.

Watt-hour meter for each 13.8-kv bus with totalizing demand meter.

Reactive kilovolt-ampere-hour meter for each 13.8-kv bus with totalizing demand meter.

Ammeter in each 13.8-kv outgoing feeder.

Watt-hour demand meter in each 13.8-kv outgoing feeder.

Annunciator

To expedite station operation, a 30-drop annunciator with audible alarm sig-

nal is installed on the duplex board and duplicated in the office of chief of maintenance, which serves to announce and identify any of the following occurrences:

Oil-circulating-pump stoppage or auxiliary-power failure at transformers 1 or 2.

Transformer differential or back-up ground-relay operation of transformers 1, 2, or the auxiliary 10,000 kva.

Low oil level in transformers 1, 2, or the auxiliary 10,000 kva.

Overtemperature in transformers 1, 2, or the auxiliary 10,000 kva.

Opening of the following circuit breakers, if the control switch was moved to the close position last:

110-kv incoming oil circuit breaker.

33-kv incoming circuit breaker.

Each of the 13.8-kv incoming-power circuit breakers.

Each of the 13.8-kv feeder breakers (the four factory-feeder circuit breakers on each bus section operate a common annunciator drop).

Operating Experience

Operating experience with this electric system has been remarkably good. The few exceptions to an otherwise perfect record were not of serious character and occasioned no loss of sleep.

Initially, some trouble was encountered in the 13.8-kv cable terminal potheads requiring that the circuits be de-energized successively, the potheads opened, and modifications made. The advantages of the secondary selective system became clearly evident during this procedure. The necessary modification work was carried out without the loss of power at any station and without the use of auxiliary makeshift power supply equipment.

A number of faults have occurred in the plug-in bus resulting from the accidental

Figure 17. View of the 13.8-kv cable feeders as they leave the main substation and pick up overhead troughs

insertion of wire or small diameter rod through the expanded metal side barriers.

Substation electric loads consistently are approaching closely the present installed capacity. A number of stations are operating at substantially full rated value while others at present generally are loaded to between 50 and 75 per cent of their ratings, but subsequent increases of 10 to 15 per cent are expected.

Summary

It may be concluded, without reservation, that the application of load-center distribution principles as herein described was responsible for an amazing reduction in material investment, principally copper and steel, compared with that which would have been required by power-distribution methods employed only a short time ago. In the planning of this project, the greatest emphasis constantly was placed on conservation of materials.

The use of compact, repetitively manufactured metal-clad, load-center unit substations do realize good economy in materials and man-hours, and at the same time incorporate simplicity and safety.

Unusual features incorporated in this system, which in themselves are responsible for large savings in material, man-hours, or both, include:

1. The application of forced-oil air-pressure cooling to the main incoming service transformers.

2. The use of overhead high-voltage feeder-cable troughs.

3. The use of spaced single-conductor low-voltage feeder design with moderate unit copper cross sections.

4. The use of 265-volt fluorescent lighting in combination with common load-center unit substations for serving power and light. (This feature alone accounts for a saving of five tons of copper and ten tons of steel compared with the most economical method of applying 120-volt fluorescent lighting.

The secondary selective system design offers a well-balanced combination of simplicity and service reliability.

The negotiation of the entire distribution system as a single unit proved highly beneficial in reducing the time of execution and insuring the best co-ordination between the several component portions.

As the supply of steel becomes less critical, it would seem reasonable to return to the use of steel construction in the outdoor station and to more effective metal-clad construction in low-voltage feeder circuits and plug-in bus.

It is the sincere hope of the authors that some of the features herein described, which have proved so beneficial in this installation, may in some small measure assist others to realize an improved more economical industrial distribution system in the future.

Inherent Errors in the Determination of Synchronous-Machine Reactances by Test

C. CONCORDIA
MEMBER AIEE

F. J. MAGINNISS
ASSOCIATE AIEE

AS PROGRESS in the design and in the calculation of performance of synchronous machines has been made it has become necessary to specify their characteristics with continually greater accuracy. The predetermination of short-circuit currents, voltage dip on sudden application of load, stability characteristics during system disturbances, excitation requirements, and many other characteristics has been made possible by the development of an adequate theory, confirmed and refined by operating and test experience. The machine characteristics commonly used to predict performance usually are specified in terms of various reactances and time constants. As the number of these quantities and the accuracy to which they must be known has increased, certain inconsistencies among methods of definition, calculation, and test have become apparent. These should ideally all result in the same value. If they differ, one naturally would be inclined to consider the test value as the true reactance. In any case in which a reactance of a particular machine is specified, a method of testing for that reactance also must be specified, and any other definition of the reactance has little practical significance. In this sense the criterion of a good method of calculating the reactance is that it predict as nearly as possible the value which will be found by the specified test method. It, of course, can be asked legitimately whether the specified reactance is the proper one in view of the use to which it is to be put, and the definition is intended to describe the reactance so as to answer this question.

The reactance found by test will be affected by errors in the method of test (as for example, nonsimultaneous short circuit of all three phases in case of three-phase short-circuit tests), by the conditions of the machine under test (as for example, the degree of saturation corresponding to the voltage used), by errors of measurement and calibration, and by the technique of measurement.

The purpose of this paper is to present the results of a comparison of the values of reactance which might be found by recommended test procedures with the values calculated by well-established formulas, as affected by the machine characteristics, and by nonsimultaneous closing of the test circuit-breaker contacts. A three-phase short-circuit test on a salient-pole synchronous machine was simulated by setting up the proper equations on the differential analyzer. The effect of saturation was not considered, and the precision of measurement of the current curves was undoubtedly greater than would be possible for an actual oscillogram so that the variations obtained were inherent in the method.

Only two of the several reactances, the direct-axis transient reactance and the direct-axis subtransient reactance, have been studied. The direct-axis short-circuit transient and subtransient time constants also have been considered but in less detail.

Definition of Machine Quantities

In the AIEE Test Code for Synchronous Machines (January 1944 revision), the definition of direct-axis transient reactance (x_d') is given as[1]

"1.840 The direct axis transient reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental direct-axis a-c component of the armature current, to this component of current under suddenly applied load conditions and at rated frequency, the value of current to be determined by the extrapolation of the envelope of the a-c component of the current wave to the instant of the sudden application of load, neglecting the high-decrement currents during the first few cycles."

In this definition the transient reactance is defined both in terms of the fundamental component of armature current and of the envelope of the a-c component of the current. The phase currents obtained after the three-phase short circuit even of an idealized machine contains second harmonics which may have appreciable magnitudes. In an actual machine having saturation, hysteresis, and eddy currents, the current may contain other harmonics as well. Even in the ideal case, with only second harmonics present, it would be extremely difficult and impractical to determine the amount of fundamental in the transient wave as is required by the first part of the definition.

Two direct-axis transient reactances are defined, the rated current value and the rated voltage value, which will differ because of saturation. However, this paper does not investigate this classification of transient reactance, as saturation effects have been neglected.

The definition of direct-axis subtransient reactance is[1]

"1.860 The direct axis subtransient reactance is the ratio of the fundamental component of reactive armature voltage, due to the initial value of the fundamental direct axis a-c component of armature current, to this component of current under suddenly applied load conditions and at rated frequency."

Measurement of Machine Reactances

Testing and measuring procedures for the determination of the direct-axis transient and subtransient reactances have been given in reference 1 and are reproduced as follows:

"DIRECT AXIS TRANSIENT REACTANCES (x_d'); DETERMINATION BY TEST

"1.843 The direct axis transient reactance is determined from the current waves of a three-phase short circuit suddenly applied to the machine operating at no load and rated speed. The direct axis transient reactance is equal to the ratio of the no load voltage to the corresponding value of the armature current given by the extrapolation of the envelopes of the a-c components of the armature current waves to the instant of the sudden application of the short circuit neglecting the high decrement currents during the first few cycles. Figures 26 and 27 (Figures 26 and 27 of the Test Code are Figures 14 and 15 of this paper) illustrate this method of determining the direct axis transient reactance.

"1.844 In plotting the current values from the oscillogram, the first peak should be plotted at the abscissa 1, and subsequent peaks numbered consecutively. The positive

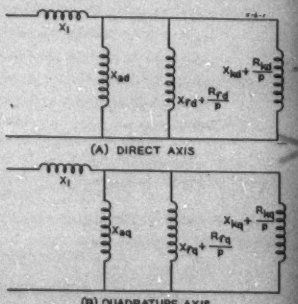

Figure 1. Synchronous-machine equivalent circuits

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C. CONCORDIA and F. J. MAGINNISS are both in the analytical division, central-station engineering divisions, General Electric Company, Schenectady, N. Y.

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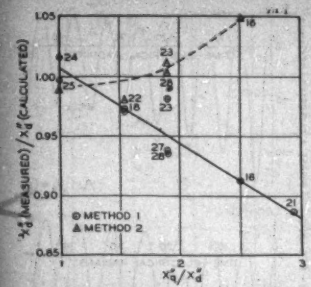

Figure 2. Effect of x_q''/x_d'' on measured subtransient reactance

peaks will be odd numbers, and the negative peaks will be even numbers or vice versa. The current values from the oscillograms should be plotted first, and then the median line and the a-c component. These curves are usually plotted on standard rectangular coordinates, and are most conveniently analyzed if the currents are expressed in per-unit values, with the unit value equal to the peak value of the rated current wave. (See Figure 26.)

"1.845 The a-c component should then be replotted on semi log scales with the current on the logarithmic scale together with a plot of the a-c component minus the sustained short-circuit current* (Curve *B*,

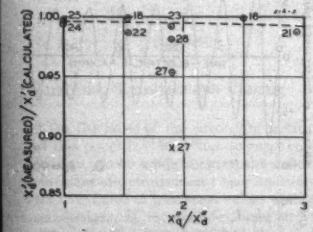

Figure 3. Effect of x_q''/x_d'' and of r_a on measured transient reactance

Case 27 has low armature resistance r_{ai} lower value obtained from first 15 cycles

Figure 27). These curves should pass through the ordinates for peak 1. Since the first peak is plotted at abscissa 1, the abscissa for the time of application of the short [circuit] is usually not at zero, but at a time which can be readily determined from the oscillogram. This zero-time line should be plotted on the semi log plot, and extrapolations of the current curves are extended to this line. It is important in plotting the first several cycles of the (AC component minus the sustained value) to choose current and time scales that will avoid a steep slope during the first three or four cycles. It will usually be found that curve *B* can be very closely represented by a straight line and a curve for several cycles at the beginning of the short circuit. The curves for the tests and analysis should be carried out for sufficient cycles to establish definitely the straight-line part of curve *B*. The difference *A* (see Figure 27) between curve *B* and the extension of the straight part to $t=O$, when plotted on the semi log scales, will also be closely represented by a straight line. (This straight line should always be plotted to pass through the ordinate for peak 1.)

"1.846 The ordinate for curve *B* at $t=O$ is equal to the sum of the ordinates at $t=O$ from the two straight lines. The ordinate for the a-c component at $t=O$ is then determined by adding the sustained short circuit current to the ordinate of curve *B* at $t=O$. The curve for the transient component plus the sustained value of the current is determined by adding the sustained short circuit current to the extended straight line part of curve *B*.

$$x_d' = \frac{e}{I'} \text{(per unit value)}$$

where

e = the open-circuit voltage of the machine immediately before the short circuit, expressed in per unit based on rated voltage

I' = per unit current from the transient component plus the sustained value at $t=0$. (Figure 27; Figure 15 of this paper)

"DIRECT AXIS SUBTRANSIENT REACTANCE (x_d''); DETERMINATION BY TEST, METHOD (1)

"1.863 The direct axis subtransient reactance is determined from the sudden short-circuit test described in paragraph 1.843

$$x_d'' = \frac{e}{I''} \text{ (per unit value)}$$

See paragraph 1.846 for "e". I'' = per-unit current from the a-c component curve at $t=0$ (Figure 27).

"1.864 Method (2). An alternate method of evaluating subtransient reactance, which may be used when the three phases are known to be short circuited simultaneously or at least within approximately ten degrees, is that based on the maximum possible asymmetrical component. Plot the three asymmetrical components (median line Figure 26 represents one of these components) on semi log scales with currents on the logarithmic scale. The peaks may be numbered as in paragraph 1.844 and the line for $t=O$ located as described in paragraph 1.845 for plotting Figure 27. Extrapolate the curves back to zero time thereby obtaining three initial values, which may be designated *a*, *b*, *c*. Lay these components off (uniform scale) along three radial lines 60° apart radiating from a point *O*, the largest of the three values being laid off on the middle line. Draw perpendiculars through the end points of each of the three lines, and the point where these perpendiculars meet determines the point *M*. In case the perpendiculars do not meet in a point, but form a small triangle, locate *M* in the approximate center of the triangle. Then the distance *OM* represents the maximum possible asymmetrical component, to the same scale as the three components on the radial lines.

$$x_d'' = \frac{e}{OM} \text{ (per unit value)}$$

See paragraph 1.846 for "e". *OM* is expressed as a per unit value, with the base equal to the peak value of the rated current wave. The ampere value of *OM* is equal to the peak value of the normal current wave multiplied by the per unit value of *OM*.

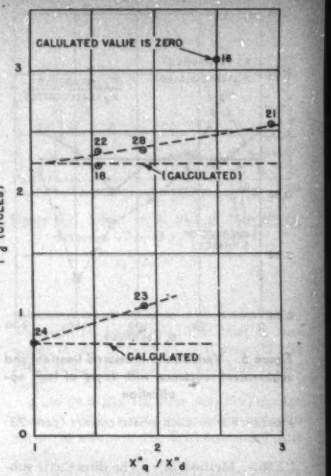

Figure 4. Effect of ratio x_q''/x_d'' on measured subtransient time constant

Table I. Machine Physical Reactances and Resistances

Case	R_a	x_{l_a}	x_{ad}	x_{fd}	x_{kd}	R_{fd}	R_{kd}	x_{aq}	x_{lq}	x_{kq}	R_{fq}	R_{kq}
22	0.00694	0.0557	1.068	0.1507	0.496	0.00068	0.037	0.414		0.3556	∞	0.035
23	0.00694	0.0557	1.068	0.1942	0.1356	0.00068	0.037	0.414		0.3556	∞	0.035
24	0.00694	0.0677	1.068	0.1942	0.1356	0.00068	0.037	0.414		0.0906	∞	0.035
18	0.00694	0.0557	1.068	0.1507	0.496	0	0.037	0.414		0.3556	∞	0.035
21	0.00694	0.0557	1.068	0.1507	0.496	0.00068	0.037	0.414			∞	∞
16	0.00694	0.0557	1.068	0.1507		0	∞	0.414			∞	∞
25	0.00694	0.0557	1.068	0.1507		0	∞	1.068	0.1507		0	∞
27	0.00231	0.0557	1.068	0.1942	0.1356	0.00068	0.01223	0.414		0.3556	∞	0.035
28	0.00694	0.0557	1.068	0.1942	0.1356	0.00068	0.01223	0.414		0.3556	∞	0.035

* The sustained short-circuit current is determined from the direct-axis synchronous impedance curve, using the armature current corresponding to the steady-state field current immediately before the machine is short-circuited.

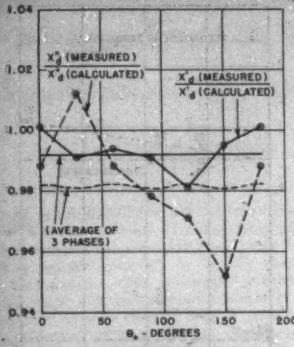

Figure 5. Variation of measured transient and subtransient reactance with angle of fault application

Reactance from each phase current (case 23)

"1.865 Method (3). The direct axis subtransient reactance may also be determined for three phase machines from a static impedance test in which a single phase voltage is impressed across two armature phase windings in series (connected for 120° phase displacement) with the field short circuited. The rotor is placed in the angular position for maximum induced field current. The subtransient reactance equals the ratio of half the applied voltage to the resulting armature current."

Several comments may be made with regard to these recommended test procedures even before the results of the present study are examined.

In this paper the envelope is taken as a smooth curve drawn through the extreme maximum and minimum points of the current-versus-time curve. This would seem to be so obvious as not to require comment except for the fact that the envelope has been defined in a different way in a previously published paper[2] on this subject.

The median line is defined only by a curve of Figure 14. This comment is again pertinent because in reference 2 the midpoint of the envelopes as there defined has been used. In the present paper the midpoint of the envelope as here defined is taken as the median line.

In the static line-to-line test for the determination of subtransient reactance the current will be sinusoidal if the voltage is sinusoidal, aside from the effect of saturation. Thus without saturation the result found from test will differ from the nominal calculated value only by the inclusion of the stator and rotor resistances. This does not imply of course that it is a better test, since in the first place saturation effects may be very important and in the second place additional test equipment is required since the short-circuit test is necessary for the transient reactance anyway.

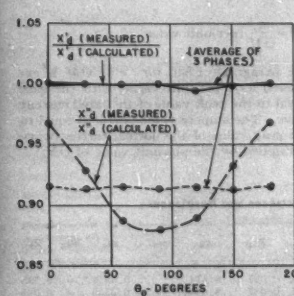

Figure 6. Variation of transient and subtransient reactance with angle of fault application

Reactance found from each phase current, case 16 (no amortisseur).

Calculation of Machine Quantities

When the per-unit mutual reactances between armature and field, armature and amortisseur, and field and amortisseur are all the same, as is assumed in the present case, it is possible to use direct- and quadrature-axes equivalent circuits for the calculation of the synchronous machine constants. These circuits are shown in Figure 2 of reference 3 and in Figure 1 here in slightly more complete form; the field resistance is not assumed zero and an additional winding is considered in the quadrature axis (see Appendix III).

The calculation of subtransient and transient reactances and time constants from these equivalent circuits is made as follows:

1. *The direct-axis subtransient reactance* x_d'' is the input impedance of the direct-axis equivalent circuit with $R_{fd}/p = R_{kd}/p = 0$. Thus x_d'' is equal to x_l in series with the paralleled value of x_{ad}, x_{fd} and x_{kd}

$$x_d'' = x_l + \frac{x_{ad}x_{fd}x_{kd}}{x_{ad}x_{fd} + x_{ad}x_{kd} + x_{fd}x_{kd}}$$

2. *The direct-axis transient reactance,* x_d' is the input impedance of the direct-axis equivalent circuit with $R_{fd}/p = 0$ and $R_{kd}/p = \infty$. Thus x_d' is equal to x_l in series with the paralleled value of x_{ad} and x_{fd}.

$$x_d' = x_l + \frac{x_{ad}x_{fd}}{x_{ad} + x_{fd}}$$

3. *Direct-axis subtransient short-circuit time constant,* T_d''. The direct-axis equivalent circuit is assumed broken in the amortisseur branch; R_{fd}/p is assumed zero; the input terminals of the equivalent circuit are short circuited. The reactance of the circuit as viewed from the terminals in the amortisseur branch is divided by R_{kd} to give T_d''.

$$T_d'' = \frac{x_{kd} + \dfrac{x_l x_{ad} x_{fd}}{x_l x_{ad} + x_l x_{fd} + x_{ad} x_{fd}}}{2\pi f R_{kd}} \text{ (seconds)}$$

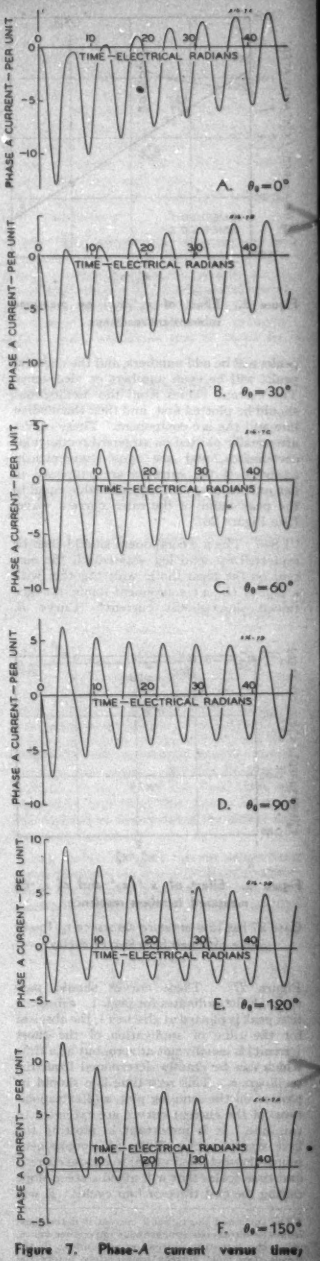

Figure 7. Phase-A current versus time, case 23

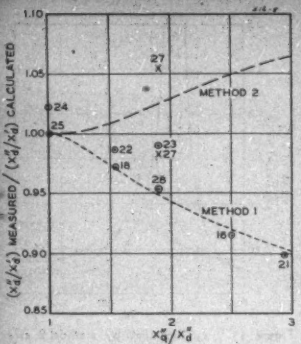

Figure 8. Variation of measured x_d''/x_d' with x_q''/x_d''

Curves are from calculations for cases of very small decrements. Points are from method 1

4. *Direct-axis transient short-circuit time constant, T_d'.* The amortisseur branch of the direct-axis equivalent circuit is assumed open circuited and the circuit is assumed broken in the field branch. The input terminals are short circuited. The reactance of the circuit as viewed from the terminals in the field circuit divided by the field resistance, R_{fd}, gives T_d'.

$$T_d' = \frac{x_{fd} + \frac{x_f x_{ad}}{x_f + x_{ad}}}{2\pi f R_{fd}} \text{ (seconds)}$$

Analysis; Simultaneous Closing

On the basis of the preceding sections of this paper it is seen that no exact comparison can be made between the defined transient and subtransient reactances and the calculated or measured values of these quantities. It is possible, however, to determine the correspondence that is to be expected between the calculated values of the reactances and the values determined by an ideal short-circuit test.

Park's equations[1] of an idealized synchronous machine (see Appendix I) were set up on the differential analyzer and the phase A current obtained for a three-phase short circuit on a machine initially running open circuited. All three phases were short circuited simultaneously; the effect of sequential closing is considered in the next section.

This A-phase current record takes the place of the oscillogram described in the sections on measurement and was analyzed as there described, giving values of x_d', x_d'', T_d', and T_d''.

For each machine studied, six solutions were obtained. These were the A-phase current for short circuits applied at each of six rotor angles, varying from 0 degrees to 150 degrees with respect to the axis of phase A in 30-degree steps. The A-phase current for a fault at 0 degrees from the axis of phase A is the negative of the current in the C phase for a fault at 60 degrees, and is also the current in the B phase for a fault at 120 degrees. It is seen then that the six solutions obtained contain all three-phase currents for each angle specified (30-degree steps). Moreover the average values of the reactances (average of the three phases for any one test) will be repeated every 60 degrees. Thus if there is a variation of this average reactance with angle of application of the fault, it is periodic with a period of 60 degrees.

The machines studied are defined in terms of the reactances and resistances of the individual stator and rotor circuits. Values of these quantities, as well as of the transient and subtransient reactances and time constants calculated from them, are given in Tables I and II.

Case 22 represents the characteristics of a machine having a rather high ratio of calculated subtransient to transient reactance, $x_d''/x_d' = 0.16/0.1878 = 0.852$, so that the equivalent amortisseur-leakage reactance $x_{kd}(=0.496)$ is large. This makes the subtransient time constant large.

Case 23 was studied to show the effect of a much smaller ratio of calculated subtransient to transient reactance, $x_d''/x_d' = 0.13/0.22 = 0.591$. One effect of the smaller x_d'' is to make x_{kd} and thus T_d'' much smaller.

Case 24 was studied to show the effect of making the rotor symmetrical for subtransient effects. The quadrature-axis

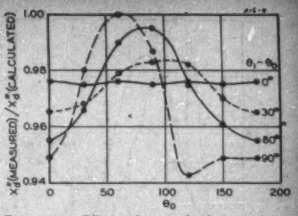

Figure 9. Effect of θ_0 and of $(\theta_1 - \theta_0)$ on measured value of x_d'', method 1

$x_q''/x_d'' = 1.5$

subtransient reactance x_q'' (calculated) was reduced to $x_q'' = 0.13$ so that it was equal to x_d'' of case 23. In case 23 the ratio of x_q''/x_d'' was 1.9, which is rather large.

Case 18 is like the first case (22) except $R_{fd} = 0$. This was considered in order to show the effect of the field transient time constant T_d'.

Case 21 was considered in order to show the effect of a large ratio of x_q''/x_d''. The quadrature-axis amortisseur was removed entirely so that $x_q''/x_d'' = 2.94$. It is otherwise the same as case 22.

In cases 16 and 25 there are no rotor resistances; the amortisseur has been completely removed and the field resistance made zero. Case 16 has an effective ratio $x_q''/x_d'' = x_q'/x_d' = 0.4697/0.1878 = 2.5$, while in case 25 $x_q''/x_d'' = x_q'/x_d' = 0.1878/0.1878 = 1.00$.

Cases 27 and 28 are to show the effect of increasing the armature and subtran-

Table II. Calculated Machine Constants

Case	x_d'	x_d''	x_d''/x_d'	x_q''	x_q''/x_d''	Cycles T_a	Cycles T_d'	Cycles T_d''
22	0.1878	0.1600	0.852	0.247	1.54	4.45	47.7	2.3
23	0.2200	0.1300	0.591	0.247	1.90	3.90	57.8	0.76
24	0.2200	0.1300	0.591	0.130	1.00	2.98	57.8	0.76
18	0.1878	0.1600	0.852	0.247	1.54	4.45	∞	2.3
21	0.1878	0.1600	0.852	0.4697	2.94	5.47	47.7	2.3
16	0.1878	0.1878	1.00	0.4697	2.50	6.15	∞	0.0
25	0.1878	0.1878	1.00	0.1878	1.00	4.30	∞	0.0
27	0.2200	0.1300	0.591	0.247	1.90	11.90	57.8	2.3
28	0.2200	0.1300	0.591	0.247	1.90	3.90	57.8	2.3

Table III. Average Measured Machine Constants

Case	x_d'	x_d''	x_q''/x_d''	T_d'	T_d''
22	0.1851	0.1557	0.841	49.9	2.35
		0.1568*	0.840*		
23	0.2183	0.1276	0.585	59.8	1.08
		0.1314*	0.602*		
24	0.2188	0.1321	0.604	60.5	0.76
18	0.1873	0.1555	0.830	∞	2.22
21	0.1855	0.1419	0.765	56.0	2.55
16	0.1876	0.1718	0.916	∞	3.09
		0.1954*	1.042*		
25	0.1872	0.1872	1.0	∞	0
		0.1859*	0.993*		
27	0.1958**	0.1215**	0.621**		
	0.2089	0.1225	0.586		
28	0.2158	0.1217	0.564	61.2	2.34
		0.1306*	0.605*		

* Denotes median method (method 2). ** Only first 15 cycles measured.

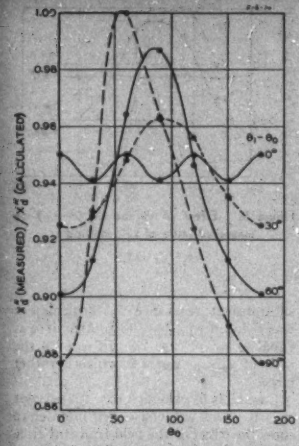

Figure 10. Effect of θ_0 and of $(\theta_1 - \theta_0)$ on measured value of x_d'', method 1

$x_q''/x_d'' = 2.0$

sient time constants. Case 28 is like case 23 except for a smaller direct-axis amortisseur resistance, designed to give a calculated subtransient time constant equal to that of case 22. Case 27 has the small direct-axis amortisseur resistance and also a small armature resistance.

Some of the results of the analyses of the short-circuit-current curves obtained on the differential analyzer for these cases are shown in Table III. This table shows the average of all six-phase currents for each case. The measured values of x_d'', x_d', and T_d'' are plotted against the calculated ratio x_q''/x_d'' in Figures 2, 3, and 4, respectively.

Figure 2 shows that for method 1 there is a tendency for the measured direct-axis subtransient reactance to decrease if the quadrature-axis subtransient reactance is increased even though no change has been made in the direct-axis rotor circuits. If the median method (method 2 of the AIEE Test Code) is used, there is no such tendency. Instead, the reactance increases slightly. As the ratio x_q''/x_d'' approaches 1.0 the measured x_d'' approaches the calculated value. All of these observations are confirmed by the results of calculations for the idealized case in which all decrements are neglected (see Figure 8).

Figure 3 shows that the ratio x_q''/x_d'' has practically no effect on the measured value of x_d'. On the other hand, the armature resistance appears to have a considerable effect. When the armature resistance is low, as in case 27, x_d' is low, presumably because of the slow decay of the second-harmonic component of current.

Figure 4 shows a slight tendency for the measured subtransient time constant T_d'' to increase with increasing x_q''/x_d'', which may be caused by the decaying second harmonic modifying the apparent subtransient decay. A striking example of this effect is shown in case 16, where there is no amortisseur, and the whole subtransient effect is produced by the second harmonic, the magnitude of the fundamental remaining constant. Case 16 also shows that the ratio of subtransient to transient reactance may be considerably less than unity even though a machine has no amortisseur.

Table IV shows the reactances obtained from the individual-phase currents and from the two sets of three-phase short circuits. Since the effects of angle should be appreciable only when $x_d'' \neq x_q''$ it is evident that the effects of the ratio x_q''/x_d'' as shown in Figures 2, 3, and 4 would be somewhat greater if the average of only three phases had been used instead of the data of Table III. However, the latter is believed to be more representative, especially in view of possible measurement errors.

Figure 5 shows measured results for the individual current waves for case 23. Figure 6 is a similar curve for case 16. The variation indicates that it is highly desirable to measure all three-phase currents and possibly to take more than one test even if there were no theoretical differences among the phases. Figure 7 shows the actual current waves for the case of Figure 5.

Figure 8 is a summary of the effect on the ratio of subtransient to transient reactance of variation in x_q''/x_d''. Since

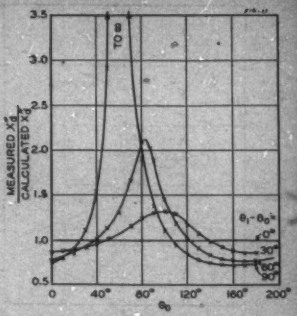

Figure 11. x_d'' measured by method 2 as a fraction of its calculated value versus θ_0

$x_q''/x_d'' = 1.5$

Figure 3 showed no appreciable effect of x_q''/x_d'' on x_d', Figure 8 may be considered to represent also the effect of x_q''/x_d'' on x_d''. The calculated variation of x_d'' neglecting decrements also is shown on Figure 8, and is seen to be in reasonably good agreement with the differential-analyzer results.

Analysis; Sequential Switching

On the basis of certain simplifying assumptions, the effect of sequential switching on the measured value of direct-axis subtransient reactance has been determined. In addition to the usual ideal synchronous machine assumptions, all machine resistances are considered to be

Table IV. Ratio of Measured to Calculated Machine Reactances

Case		θ_0 = 0°	30°	60°	90°	120°	150°	Three-Phase Average for Fault at θ_0 = 0	30°	Average
22	x_d'	0.988	0.996	0.980	*	0.976	0.989	0.981	0.993	0.986
	x_d''	0.988	0.970	0.959	*	0.962	0.988	0.970	0.979	0.972
								0.983**	0.976**	0.980**
23	x_d'	1.001	0.991	0.994	0.991	0.981	0.995	0.992	0.992	0.992
	x_d''	0.988	1.012	0.988	0.978	0.971	0.952	0.982	0.981	0.982
								1.013**	1.008**	1.011**
24	x_d'	0.992	0.992	0.996	0.990	1.001	0.995	0.996	0.992	0.994
	x_d''	0.985	1.069	1.036	1.002	1.004	1.002	1.008	1.024	1.016
18	x_d'	0.997	1.000	1.002	0.997	1.001	0.995	1.000	0.997	0.999
	x_d''	0.998	0.979	0.960	0.951	0.960	0.979	0.973	0.970	0.971
21	x_d'	1.014	0.991	0.971	0.970	0.970	1.008	0.985	0.990	0.987
	x_d''	0.904	0.909	0.868	0.859	0.874	0.906	0.883	0.891	0.887
16	x_d'	1.001	1.000	1.000	1.000	0.995	0.999	0.999	1.000	0.999
	x_d''	0.968	0.929	0.887	0.880	0.890	0.932	0.915	0.914	0.914
								1.014**	1.081**	1.048**
25	x_d'	1.000	1.000	1.000	0.997	0.992	0.992	0.997	0.996	0.997
	x_d''	1.000	1.000	1.000	0.997	0.992	0.992	0.997	0.996	0.997
								0.995**	0.981**	0.988
27	x_d'***	0.951	0.893	0.854	0.839	0.857	0.947	0.887	0.893	0.890
	x_d'	0.973	0.963	0.961	0.924	0.931	0.973	0.955	0.953	0.954
	x_d''	0.983	0.975	0.934	0.908	0.880	0.950	0.932	0.944	0.938
28	x_d'	0.975	0.974	0.991	0.991	0.990	0.964	0.985	0.976	0.981
	x_d''	0.997	0.948	0.922	0.901	0.909	0.940	0.943	0.930	0.936
								0.998**	1.008**	1.003

* Results for this point are questionable and are not included in average values.

** Denotes method 2. *** Only first 15 cycles measured.

zero. The three-phase currents[4] (see Appendix II) have been plotted for values of θ_0, the angle at which the first two phases are short circuited, and of $\theta_1 - \theta_0$, the angle of delay between the short circuiting of the first two phases and of the third phase. Since there is no decay of current, the peak-to-peak phase currents may be used to determine the direct-axis subtransient reactance. As in the previous section of this paper, the direct-axis subtransient reactance has been determined by the two methods described there.

Method 1

Figures 9 and 10 give the ratio of measured reactance* (differential-analyzer results), to calculated reactance for values of x_q''/x_d'' of 1.5 and 2.0, respectively. (Sequential switching will not affect the measured reactance for $x_q''/x_d'' = 1$.) For a delay in closing of the third phase of 60 electrical degrees, the maximum variations in measured reactance can be four per cent for $x_q''/x_d'' = 1.5$ and 8.5 per cent for $x_q''/x_d'' = 2.0$. These variations are much larger than those due to the subtransient saliency alone as discussed under simultaneous switching.

Method 2

The theoretical discrepancy ratio as defined in reference 4 is the ratio of x_d''

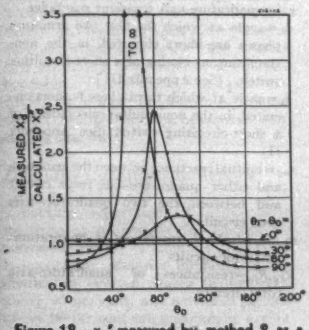

Figure 12. x_d'' measured by method 2 as a fraction of its calculated value versus θ_0

$x_q''/x_d'' = 2.0$

measured by method 2, except that only the direct component of current is used, to its defined value. This neglects the effect of the second-harmonic current on the measured value of the asymmetrical component. In this paper x_d'' is measured by method 2 considering the total current. Figures 11 and 12 show the ratio of measured to calculated reactance for values of x_q''/x_d'' of 1.5 and 2.0, respectively for various values of θ_0 and $\theta_1 - \theta_0$. A similar set of curves for $x_q''/x_d'' = 1.0$ is given in Figure 3 of reference 4.

* By measured reactance is meant that value which would be obtained by analysis of an oscillogram of the short-circuit current of an ideal synchronous machine with characteristics corresponding to the assumptions.

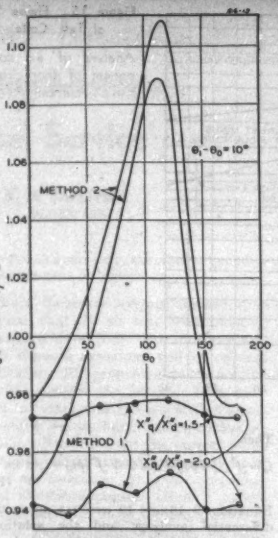

Figure 13. Effect of θ_0 and of x_q''/x_d'' on measured value of x_d''

It has been noted in the section of this paper on simultaneous switching that in general method 2 gives results somewhat closer to the calculated subtransient reactance than does method 1. From this it should not be inferred that method 2 is generally superior. The difficulty in adjusting the circuit breaker to close the three phases within ten degrees as required by the standards as well as the difficulty in determining from the oscillogram whether or not this angle is less than ten degrees are both considerable. Moreover, it is seen from Figure 13 that even for so small a delay angle as ten degrees, the results obtained by this method are far inferior to those obtained by method 1.

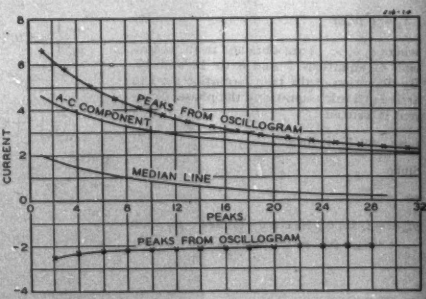

Figure 14. Figure 26 of Test Code

Peak values of instantaneous short-circuit currents and deviation of a-c component

Conclusions

From the results obtained in this study the following conclusions may be drawn:

1. The direct-axis subtransient reactance and time constant as measured by any short-circuit test method so far proposed depends not only on the characteristics of the direct-axis rotor circuits, but also on those of the quadrature axis.

2. Method 1 of the AIEE Test Code should be used in the measurement of direct-axis subtransient reactance to the exclusion of method 2, the asymmetrical method.

3. There may be a considerable variation of the magnitude of the individual-phase currents with angle of fault application. This, in conjunction with possible measurement errors, makes it very important to use the average obtained from all three-phase currents of any one test, and highly desirable to use the results of more than one test.

4. Since the measured subtransient reactance may be low and the measured transient reactance may be about right in comparison with calculated values, the ratio of subtransient to transient reactance may be low. In particular, even with no amortisseur the measured ratio x_d''/x_d' is appreciably smaller than unity.

5. It often may be necessary to use considerably more than 15 cycles in order to obtain the correct value of transient reactance, especially if the armature resistance is low.

6. The maximum difference in closing angle should be limited to as low a value as possible.

7. The short-circuit test methods given in the AIEE Test Code approach, but are not in entire agreement with, the definition of subtransient reactance. It would, moreover, be impracticable if not impossible to test directly for the defined subtransient reactance.

Appendix I

On the assumption of constant unit rotor speed, Park's equations[5] for an ideal synchronous machine may be written

$$e_d = p\psi_d - ri_d - \psi_q \quad (1)$$

$$e_q = p\psi_q - ri_q + \psi_d \quad (2)$$

$$\psi_d = G(p)E - x_d(p)i_d \quad (3)$$

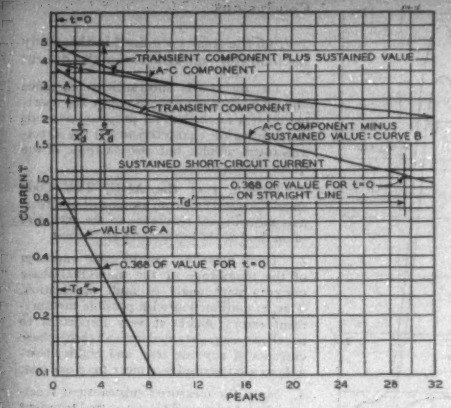

Figure 13. Figure 27 of Test Code

Analysis of a-c component of short-circuit current

$$\psi_q = -x_q(p) i_q \tag{4}$$

If a simultaneous three-phase short circuit is applied at the terminals of a machine initially running open-circuited with no change in the applied field voltage, these equations reduce to

$$0 = p\psi_d - r i_d - \psi_q \tag{5}$$

$$-e_m = p\psi_q - r i_q + \psi_d = -1.0 \tag{6}$$

$$\psi_d = -x_d(p) i_d \tag{7}$$

$$\psi_q = -x_q(p) i_q \tag{8}$$

where $x_d(p)$ and $x_q(p)$ are the operational input impedances of the circuits of Figure 1.

After reduction to suitable form for the differential analyzer, these become

$$p i_d = \psi_q + r i_d \tag{9}$$

$$\psi_d = \int p\psi_d dt \tag{10}$$

$$p\psi_q = -1.0 - \psi_d + r i_q \tag{11}$$

$$\psi_q = \int p\psi_q dt \tag{12}$$

$$p i_d = a p\psi_d + b\psi_d + c i_d + \int (d i_d + e\psi_d) dt \tag{13}$$

$$i_d = \int p i_d dt \tag{14}$$

$$p i_q = f p\psi_q + g\psi_q + h i_q + \int (j i_q + k\psi_q) dt \tag{15}$$

$$i_q = \int p i_q dt \tag{16}$$

where $a, b, \ldots k$ are obtained in the reduction of equations 7 and 8 to 13 and 15. By definition of the transformation used to arrive at Park's equations, the phase A current is written

$$i_a = i_d \cos\theta - i_q \sin\theta \tag{17}$$

Since

$$p\theta = 1$$

$$p i_a = -i_d \sin\theta + p i_d \cos\theta - i_q \cos\theta - p i_q \sin\theta$$
$$= -(i_d + p i_q)\sin\theta + (p i_d - i_q)\cos\theta \tag{18}$$

Then

$$i_a = \int (i_d + p i_q) d \cos\theta + \int (p i_d - i_q) d \sin\theta \tag{19}$$

Equations 9–16 and 19 were set up on the differential analyzer and the solutions referred to in the text were obtained.

Appendix II

In determining direct-axis subtransient reactance for cases of nonsimultaneous switching, peak-to-peak values of the three-phase currents have been obtained by numerical substitution in equations 1 of reference 4. These are

$$i_1 = \frac{I_0}{x_d''}\left\{\cos\theta - \frac{k_0}{\sqrt{3}n}[(1+n) - (1-n)\cos 2\theta] - \frac{k_1}{\sqrt{3}n}\left[\frac{1+n}{2} + (1-n)\cos(2\theta+120°)\right]\right\}$$

$$i_2 = \left\{\frac{I_0}{x_d''}\cos(\theta-120°) + \frac{k_0}{\sqrt{3}n}\left[\frac{1+n}{2} + (1-n)\cos(2\theta-120°)\right] - \frac{k_1}{\sqrt{3}n}\times\left[\frac{1+n}{2} + (1-n)\cos 2\theta\right]\right\}$$

$$i_3 = \left\{\frac{I_0}{x_d''}\cos(\theta+120°) + \frac{k_0}{\sqrt{3}n}\times\left[\frac{1+n}{2} + (1-n)\cos(2\theta+120°)\right] + \frac{k_1}{\sqrt{3}n}[(1+n) - (1-n)\cos(2\theta-120°)]\right\}$$

where

$$n = x_q''/x_d''$$

and

$$k_0 = \sin(\theta_0 + 120°)$$

$$k_1 = \sin\theta_1 + [\sin(\theta_1+120°) - \sin(\theta_0+120°)]\times \frac{\frac{1+n}{2} + (1-n)\cos(2\theta_1+120°)}{1+n-(1-n)\cos(2\theta_1-120°)}$$

and where the phase rotation is 1, 2, 3, and line 3 is the last one short-circuited, at $\theta = \theta_1$, after previous short circuit of lines 1 and 2 at $\theta = \theta_0$.

It will be noted that a typographical error in these equations in the reference has been corrected.

Appendix III. Nomenclature

See also Figure 1 and Appendixes I and II.

x_d'' = direct-axis subtransient reactance
x_d' = direct-axis transient reactance
x_l = armature-leakage reactance
x_{ad} = mutual reactance between the armature and field, field and direct-axis amortisseur, and armature and direct-axis amortisseur
x_{fd} = field-leakage reactance
x_{kd} = direct-axis amortisseur leakage reactance
R_{fd} = field resistance
R_{kd} = direct-axis amortisseur resistance
T_d'' = direct-axis subtransient short-circuit time constant
T_d' = direct-axis transient short-circuit time constant
x_q'' = quadrature-axis subtransient reactance
x_q' = quadrature-axis transient reactance
θ_0 = angle at which the first two armature phases are short circuited, in the nonsimultaneous closing of a short-circuiting switch. (See Appendix II)
θ_1 = angle at which third phase is short-circuited, in the nonsimultaneous closing of a short-circuiting switch (See Appendix II)
x_{aq} = mutual reactance between the armature and either quadrature-axis rotor circuit and between the two quadrature-axis rotor circuits
x_{kq}, x_{fq} = leakage reactances of quadrature-axis rotor circuits
R_{kq}, R_{fq} = resistances of quadrature-axis rotor circuits

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Electrolytic Corrosion—Methods of Evaluating Insulating Materials Used in Tropical Service

B. H. THOMPSON
NONMEMBER AIEE

K. N. MATHES
MEMBER AIEE

Synopsis: The selection of insulating materials to guard against electrolytic corrosion has become increasingly important as the use of electric devices in the tropics has increased. Moisture conditions in the tropics are described, and means for producing such conditions in the laboratory are considered. The visual, corrosion-current, and water-extract conductivity methods for studying electrolytic corrosion are described. Typical results for a number of different materials are given.

THE EFFECT of moisture on electric windings is a factor to be considered for successful performance in the field. In some cases moisture absorption in the insulating material produces a direct dielectric failure between turns, between phases, or to ground. In others moisture absorption may produce leakage currents which electrolytically decompose the conductor and result in open rather than in short-circuited windings. This destructive effect has been named electrolytic corrosion. Electrolytic corrosion accounts for a large proportion of failures caused by moisture in apparatus containing fine wire.[1]

Humidity Conditions in Service

Because absorption of atmospheric moisture is responsible for electrolytic corrosion, a study of humidity conditions is important. Relative humidity in the continental United States seldom rises above 95 per cent, and extended periods above 90 per cent are uncommon, except possibly on the Gulf Coast. In the tropics moisture conditions are much more severe. During the rainy season relative humidity above 95 per cent is common. Table I gives values obtained for Rangoon, Burma. The figures for the worst month, August, can be summarized as follows:

1. For eight hours a day the relative humidity is 97 per cent or higher,
2. For 13 hours a day the relative humidity is 95 per cent or higher.

Since these are average figures, it is obvious that the air very often must be saturated completely with moisture and that exposed apparatus will be covered with dew. Rangoon is probably not the wettest place in the tropics. It is, however, a location in the tropics for which humidity values have been recorded officially. Reports from the tropics of 30 feet of rainfall in two months and seas of mud are frequent. It is not surprising that electric apparatus often is soaked completely with water for long periods of time. The windings often dry out only when heated or when exposed directly to the sun.

Even in temperate climates moisture condensation may occur on apparatus chilled during aircraft flight at high altitudes. This water may be forced even into electric windings by pressure changes resulting from subsequent changes in altitude. Serious damage may occur, if this absorbed water freezes and cracks the insulation.

Aircraft apparatus will be exposed to high humidities caused by changes in altitude for only relatively short periods of time, unless the apparatus operates in closed containers in which moisture collects. Consequently, flight conditions in temperate climates are much less severe than tropical conditions. Of course, aircraft in the tropics will be exposed to tropical conditions of moisture while grounded. The wet apparatus then would, in subsequent flight, be exposed to the temperature and pressure changes accompanying changes in altitude.

Humidity Conditions in the Laboratory

Laboratory moisture tests should approximate service conditions as closely as possible.

To simulate the worst tropical conditions, a laboratory condition of 100-per-cent relative humidity, plus dew at 35 degrees centigrade (95 degrees Fahrenheit) has been adopted. This condition is reproducible and is obtained easily with inexpensive equipment. Water in the bottom of a heat-insulated box is heated

Figure 1. Refrigerator box used for obtaining a humidity of 100 per cent plus dew at 35 degrees centigrade

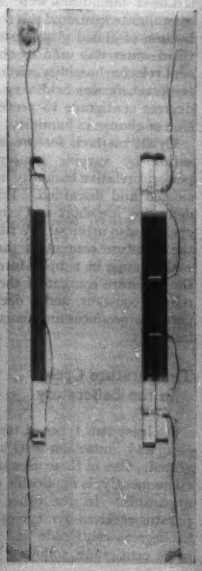

Figure 2. Glass-rod samples used in the visual method of evaluating the corrosiveness of insulating materials

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B. H. THOMPSON and K. N. MATHES are in the general engineering laboratory, General Electric Company, Schenectady, N. Y.

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Figure 3. Photomicrograph of electrolytic corrosion of copper wire

with an immersion heater. The water vapor rising from the surface of the warm water will condense as a fine dew throughout the slightly cooler space in the box. A large refrigerator box (Figure 1) is tipped back sufficiently to hold water in the bottom and at the same time to allow condensed water to run off the top surface without dripping. The box is located in a room held at 25 ± 1 degree centigrade, and sufficient heat is supplied at a constant rate to the water to maintain an air temperature of 35 degrees centigrade. This equipment has been used for most of the work to be described.

Lower humidities were obtained with appropriate saturated salt solutions in the bottom of closed glass desiccators. Distilled water was used to obtain 100-per-cent relative humidity without dew. The temperature was held very closely at 25 degrees centigrade to prevent condensation or change in humidity.

Cyclic methods for producing condensation by varying temperature at 95-per-cent relative humidity have been considered and discarded. Periods of condensation are short and erratic. Such a cycle is also artificial. With this method the moisture content of the air changes with change in temperature. In service the moisture content of the air tends to remain constant, and a decrease in temperature produces an increase in relative humidity.

Temperature Cycles in the Laboratory

At least two types of temperature cycling and immersion tests have been suggested. One of these uses salt water and, consequently, is applicable only to sealed apparatus. In the other test the apparatus receives five cycles between plus 85 degrees centigrade and minus 65 degrees centigrade, followed by immersion in water which is cycled five times between room temperature and 71 degrees centigrade in 24 hours. This test is difficult to interpret.

A number of tests have been made in which simple temperature cycles preceded exposure to 100-per-cent relative humidity plus dew. Such temperature cycles will open up brittle insulation subject to thermal shock. It is the authors' opinion that subsequent exposure to 100-per-cent relative humidity plus dew is sufficiently severe and easier to interpret than water immersion.

Corrosion Tests on Insulating Materials

It has been recognized that the best approach to corrosion-free apparatus lies in the use of insulating materials which will be as free as possible of corrosion effect.[1] Factors influencing electrolytic corrosion are discussed in the appendix. The following sections describe three methods developed to evaluate corrosion-inducing characteristics of insulating materials.

Visual Test

Two types of glass-rod samples are used for the visual evaluation of corrosiveness. One uses a single rod and the other two rods. The single rods are wrapped with the sheet material to be tested. They also may be used for testing varnish films by forming the varnish film on the rod. A sheet material like cellulose acetate, however, tested at 100-per-cent relative humidity plus dew may collect a pool of water at the edge of the sheet. To help overcome this condition the double-rod sample is used (right side of Figure 2). The sheet material is wrapped around the two rods in the form of a figure eight so that no edge appears at the surface. Two windings of three close turns of 0.010-inch bare copper wire around the rods are spaced approximately one inch apart at the center of the rods. The sample is hung vertically at the required humidity and 120-volts direct current applied between windings. The condition of the positive wire is examined periodically with a microscope.

The test is run for seven days. The test is discontinued in a shorter time, if the positive wire corrodes completely open Corrosion usually starts with slight marking of the copper or slight discoloration of the insulating material, followed by mechanical roughening, which leads eventually to deep pitting. The initial marking on the wire is difficult to photograph, but surface roughening and a deep pit are shown in Figure 3.

The following method of comparing corrosion resistance of insulating materials has been found convenient:

Appearance Under a 20-Power Microscope	Rating
Coloring or corrosion first appears in 1 day	Very corrosive
Coloring or corrosion first appears in 2 days	Poor
Coloring or corrosion first appears in 3 days	Fair
Coloring or corrosion first appears in 7 days	Good

At the end of seven days the plus electrode wire is removed and examined under a 20-power microscope. If only faint markings are visible on the surface of the wire, the material is rated excellent. Such results should be obtained at a test humidity representing expected service humidities. Extrapolation from a lower to a higher humidity has been found to be misleading, for example, a rating of excellent at 95-per-cent relative humidity has with our present knowledge, little meaning at tropical conditions of 100-per-cent humidity plus dew. Tests on materials, of course, are only comparative and cannot be used to predict life of assembled apparatus.

The physical appearance of the positive wire is, of course, only a qualitative measurement, and the rating depends somewhat upon the judgment of the observer. Our efforts to use the wire breaking strength as a quantitative measure at a humidity of 100 per cent plus dew have been unsuccessful for the following reasons.

1. When sufficient corrosion has been obtained to affect breaking strength significantly, the wire may be pitted severely at one place or less severely at several places.

Figure 4. Holder for corrosion-current measurements

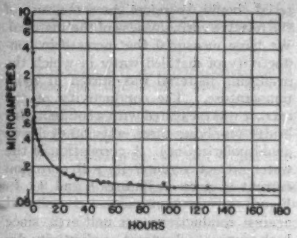

Figure 5. Corrosion-current–time curve for cellulose-acetate cloth adhesive tape

Glass-rod-type specimen. Volts—120 direct current on continuously. Humidity—100 per cent (no dew). Temperature—25 degrees centigrade

Consequently, a large number of samples will be needed to give a significant result.

2. A very long time on test may be needed to produce a measurable decrease in the breaking strength of the wire. It is estimated that three months would be required to produce a detectable change in breaking strength for a sample that would just make the rating of excellent by the visual method.

An adaptation of the glass-rod test is used for rigid insulating materials—the copper wire electrodes are wrapped directly on the sample. It has been found desirable to roughen or cut at least one edge of molded material to remove the "skin." The roughened edge represents the machined or sanded surfaces often encountered in use.

Corrosion-Current Method

Electrolytic corrosion occurs when current flow makes available ionic constituents to attack the metal. Therefore it should be possible to obtain an indirect measure of electrolytic corrosion by measuring the magnitude of the corrosion current providing that:

1. All the current measured does contribute to corrosion—the ions carried to the positive wire are able to attack it. (Platinum wire resists such attack.)

2. The decomposition products of corrosion at the wire do not form a tight insulating surface, which would eventually prevent current flow.

Actual tests have shown that copper wire on a large number of different insulating materials fulfills the above conditions.

All tests on insulating materials are made with copper. Aluminum, silver, nickel, and nichrome are known to be attacked, but a different rate may be expected for different metals.

Guarded sample holders (Figure 4) have been constructed to make current measurements on sheet insulating materials. (Varnishes have been evaluated by testing them as coatings on films known to be low in corrosiveness by previous test.) The sample is exposed to the desired humidity for a sufficient length of time to obtain equilibrium (usually 24 hours). The current resulting from 120-volts direct current across the sample is measured with a galvanometer capable of detecting 0.0001 microampere. When voltage is applied to a sample of sheet insulating material, the current decreases rapidly at first and then more slowly as a function of time (Figure 5). A series of current–time curves are plotted in Figure 6. The decrease in current after the voltage has been removed seem to be typical polarization and appear to be functions of the amount of corrosion

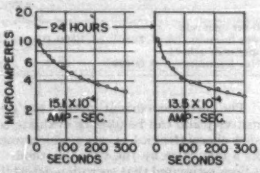

Figure 6. Corrosion current during five-minute applications of voltage at 24-hour interval

Cellulose-acetate cloth adhesive tape. Glass-rod-type specimen. Volts—120 direct current. Temperature—25 degrees centigrade. Humidity—100 per cent (no dew)

that has taken place. The more corrosive materials show the largest initial current and the greatest decrease of current with time. At first thought it seems necessary to obtain the current–time curve in order to make a comparison between materials. However, the initial current is influenced only by the characteristics of the material, and that which follows is reduced

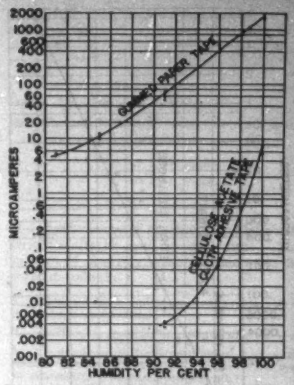

Figure 7. Effect of humidity at 25 degrees centigrade on corrosion current

Glass-rod-type of specimen

by polarization. The initial current is, therefore, the value giving the comparison between materials. Since it is rather difficult to measure the initial current, the current value 15 seconds after the voltage has been applied is used instead.

Because the corrosion-current method is indirect, it becomes necessary to calibrate it in terms of the visual-corrosion test. Table II shows a comparison of initial-corrosion current and integrated actual corrosion current–time with visual corrosion. Time was adjusted by trial to obtain a point at which pitting or roughening of the wire had just become visible microscopically. The similarity between the current–time values for a definite amount of corrosion is striking

Table I. Monthly Mean of the Relative Humidity (Per Cent) for Each Hour at Rangoon

Values Obtained From India Meteorological Department, Poona, India

Hour	January	February	March	April	May	June	July	August	September	October	November	December
Midnight	85	81	83	82	90	96	96	97	97	96	93	90
1	86	83	86	84	91	97	96	97	96	97	93	90
2	86	86	88	85	92	97	97	97	97	97	94	91
3	88	86	90	88	92	97	97	97	97	97	94	92
4	89	87	92	90	93	97	97	98	97	97	94	92
5	89	91	93	90	93	97	97	97	98	97	94	93
6	89	91	93	91	94	97	97	98	98	97	95	93
7	90	91	93	88	91	96	97	97	97	97	93	92
8	83	82	87	81	86	93	95	96	94	93	89	84
9	73	73	75	70	80	89	91	93	90	87	82	77
10	64	63	63	61	73	87	88	91	88	83	77	69
11	53	49	49	53	69	85	86	88	85	80	71	61
Noon	47	40	41	48	68	85	84	88	85	78	68	59
13	43	36	35	45	68	84	82	88	84	75	66	57
14	41	34	35	46	68	83	83	88	83	75	66	58
15	40	34	37	48	70	85	86	89	84	74	66	57
16	43	38	43	53	73	88	87	89	86	73	69	60
17	48	44	48	57	75	88	91	90	89	81	77	67
18	61	53	59	65	79	91	92	93	91	88	86	76
19	68	63	67	71	83	93	93	94	93	91	89	82
20	74	71	73	74	86	94	94	95	94	93	91	85
21	79	73	76	77	87	95	95	96	95	94	92	87
22	82	78	77	79	88	95	95	96	96	95	92	89
23	84	80	79	80	89	96	95	96	96	96	93	90
Mean	70	67	69	71	82	92	92	94	92	89	84	79

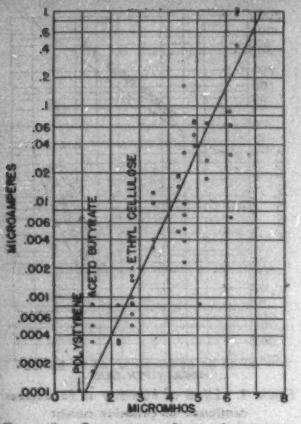

Figure 8. Comparison of corrosion current with conductivity of water extract for films

The corrosion current was measured at a humidity of 100 per cent plus dew at 35 degrees centigrade. The conductivity of water extract is in micromhos per centimeter for 100 square inches per liter of water. All films are cellulose acetate except the three marked otherwise

in view of the wide difference between conditions and samples shown in Table II.

We have found that 0.02-microampere initial current with the holder shown in Figure 4 compares with the grade of excellent of the visual method.

Table III shows typical results for a number of sheet and fabric insulations at 100-per-cent relative humidity plus dew at 35 degrees centigrade. Conclusions can be drawn as follows:

1. A single class of materials such as cellulose acetate may possess a wide range of corrosion-inducing characteristics.

2. The materials which are wet by water—cloth, paper, and cellophane—are considerably more corrosive than the water-resistant foils like acetates and polystyrene.

3. No great difference between the various untreated fabrics is apparent at 100-per-cent relative humidity plus dew.

The above conclusions apply for a humidity of 100 per cent plus dew at 35 degrees centigrade. The relative corrosiveness for the various materials may be widely different at lower humidities.

Table IV and Figure 7 have been included to show the reliability and the range of the corrosion-current method. Corrosion currents for a gummed-paper tape and an adhesive-backed cellulose-acetate fabric have been compared as a function of humidity. Conclusions follow.

1. The consistency of results is good—except for two values, one of which was obviously in error, maximum and minimum values were within two to one.

2. The ratio between the gummed paper and the acetate adhesive tape is not constant with change in humidity. The following tabulation illustrates the danger of predicting corrosion results at higher humidity from results at a low humidity or vice versa.

Corrosion Current—Microamperes

	A—Cellulose-Acetate Fabric Adhesive Tape	B—Gummed-Paper Tape	Ratio B/A
100-per-cent relative humidity	7.79	1,600.0	217
91-per-cent relative humidity	0.00499	63.7	12,800

3. The corrosion-current method has great sensitivity and can be used to evaluate corrosion characteristics in cases which would take a long time by the visual method. It has been estimated that corrosion detectable by the current method would require nearly four years exposure to be detected by the visual method.

Water-Extract Conductivity Test

The magnitude of the corrosion current depends upon the quantity of free ions available for carrying the current. A measure of the relative amounts of ionizable constituents in the insulating material should, therefore, be a measure of the relative corrosiveness of the material. We have measured the increase in conductivity of distilled water in which the insulating material was stirred at room temperature. The conductivity of the extract was measured with a conductivity bridge (applying three volts, 60 cycles to avoid polarization). A correlation of the water-extract conductivity with corrosion current is given in Figures 8 and 9. In Figure 8 corrosion current is plotted against conductivity per unit area, since both current and extract conductivity depend in this case primarily on area. The current per mil thickness and the extract conductivity per unit volume are the controlling factors for materials which wet easily. The correlation would be expected to hold only at 100-per-cent relative humidity plus dew.

The water-extract conductivity test requires relatively little apparatus. The method should be useful in quality control, particularly if care is used to insure reasonable accuracy.

Conclusions

High relative humidity with moisture condensation is a characteristic tropical condition. This condition can be simulated easily in the laboratory and should be used to test insulation materials designed for tropical application. Materials should be tested, of course, in the form in which they are used in the completed device.

Table II. Correlation of Corrosion Ampere-Seconds and Extent of Corrosion of Plus Electrode Wire on Glass-Rod Type of Corrosion Specimen

Material	Humidity, Per Cent	Temperature, Degrees Centigrade	Initial Current, Microamperes	Duration of Test, Hours	Ampere-Second	Extent of Corrosion of Plus Wire With 40 Times Magnification
Black cellulose-acetate fabric adhesive tape	100+dew	35	120	1.0	0.18	Scattered small pits visible
White cellulose-acetate fabric adhesive tape	100+dew	35	92	7.0	0.18	Color in tape just visible; small pits all along the plus wire visible
Gummed-paper tape	96	24	420	0.33	0.23	Color in paper visible; depth in corrosion visible
Gummed-paper tape	96	24	410	0.33	0.21	Color in paper visible; depth in corrosion visible

Table III. Corrosiveness of Various Materials at a Humidity of 100 Per Cent Plus Dew at 35 Degrees Centigrade. Measured by the Corrosion-Current Method

Material	Thickness, Mils	Corrosion Current, Microamperes		
		Average	Minimum	Maximum
Polystyrene film	1.1	<0.0001		
Cellulose-acetate film *A*	1.1	0.0005	0.0002	0.0008
Cellulose-acetate film *B*	5.0	0.056	0.039	0.070
Cellulose-acetate film *C*	10.0	0.86	0.43	1.07
Continuous-filament glass cloth	4.3	340	240	430
Cellulose-acetate cloth	7.0	290	240	340
Cotton cloth	9.6	420	310	500
Cellophane film	0.75	680	500	800
Kraft paper *A*	0.6	200	180	220
Kraft paper *B*	6.5	1,470	1,360	1,600

Three types of test have proved useful in evaluating corrosiveness of insulating materials.

1. The visual test gives qualitative results. Microscopic examination is used to increase sensitivity. The rating depends somewhat upon the judgment of the observer. The visual test may be used at any humidity.

2. The corrosion-current test is quantitative and the most sensitive method. Corrosion, which may take considerable time to show up under a microscope, can be quickly evaluated. The corrosion-current method is also applicable at any humidity.

3. The water-extract test is quantitative but limited in correlation to corrosion tests made at 100-per-cent relative humidity plus dew. Considerable care is necessary to obtain accurate results.

The corrosive nature of insulating materials differs widely. In fact a single class of materials may possess a wide range of corrosion-inducing characteristics. No class of materials yet has been found to be completely noncorrosive. Consequently, corrosion characteristics should be determined and controlled by test. Such tests form a basis for design.

Appendix. Factors Influencing Electrolytic Corrosion

If a direct potential be applied between two copper wires separated by an insulating material, current will flow. At low humidities this current is usually exceedingly small. As humidity is increased, moisture may be absorbed within the insulating material and adsorbed on the surface. In the presence of the free water the current increases markedly for most insulating materials. If the air become saturated with moisture, the water may condense on the surface to form an additional path for current flow. As current flows, the copper at the positive wire is ionized and combines with the acidic or oxidizing component of the electrolyte.

Pure water is a good insulator, but water will dissolve avidly at least small amounts of a great variety of substances. These materials ionize to form an electrolyte. The sources of electrolyte in insulation can be listed as follows:

1. Water-soluble constituents on the surface or in the body of the material.

2. Chemical hydrolysis, for example, of glue.

3. Electrochemical decomposition to give water soluble constituents—cellulose, for example, may be oxidized to give acidic components.[1]

4. Change due to heat:

(*a*). To give water-soluble decomposition products

(*b*). To produce sweating of water-soluble constituents to the surface.

(*c*). To permit penetration of water into the body of the material which may contain soluble materials.

5. Presence of fungus, which produces water-soluble products in their growth process.

When liquid water condenses on the surface, it may tend to form tiny drops or spread to a continuous film as shown schematically in Figure 10. The angle of contact at the interface between water and the solid insulating material is called the contact angle. This angle is a measure of the tendency of water to spread or to collect in droplets (the tendency to collect in droplets is associated with high-contact angle). Disconnected droplets, even though they contain an electrolyte possess relatively high resistance to current flow. In contrast a continuous water film containing electrolytes will conduct current readily.

Insulation in devices which have been varnish treated or coated may not reach a moisture content in service corresponding to the atmospheric humidity because:

1. The length of the period of idleness for the insulation to reach a stable moisture condition increases with the delay in the entrance of moisture.

2. Varnished-treated insulation, even though poorly treated, will not take on as much moisture as the untreated material.

In other words, when voltage is applied in service the insulation is at a moisture condition corresponding to some humidity below the atmosphere humidity to which the device is exposed. For such applications it may be desirable to make the corrosion test on the insulation at a humidity below the service conditions of humidity.

Since so many factors may produce electrolytic corrosion, only actual test can be the deciding factor.

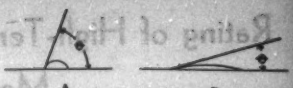

Figure 10. Diagram showing the angles of contact, θ, of a drop of water to an insulating material

A.—A high angle
B.—A low angle

Table IV. Corrosion Currents for an Acetate-Fabric Tape and a PaperTape at Various Humidities

Specimens on Glass Rods, Spacing Between Copper-Wire Electrodes One Inch, Voltage 120 Volts Direct Current. Current Measured 15 Seconds After Application of Voltage. Current in Microamperes

Humidity, Per Cent Degrees Centigrade	100 Plus Dew 35	100 25	96 25	91 25	85 25	81 25
Cellulose-acetate fabric adhesive tape						
	192	5.37	0.0415	0.00344		
	165	7.50	0.0553	0.00420		
	144	7.67	0.0679	0.00789		
	116	9.23	0.0532	0.00445		
	51.9*	7.14	0.0457			
	226	9.81	0.0503			
Average	169	7.79	0.0523	0.00499		
Gummed-paper tape						
	4,480	1,630	464	57.0	12.6	4.74
	5,140	1,720	503	72.1	10.9	4.89
	5,340	1,740	512	51.1	10.9	4.82
	5,910	1,660	372	68.4	9.5	5.32
				68.7		
				64.7		
Average	5,220	1,690	463	63.7	10.8	4.94

* Not used in obtaining the average.

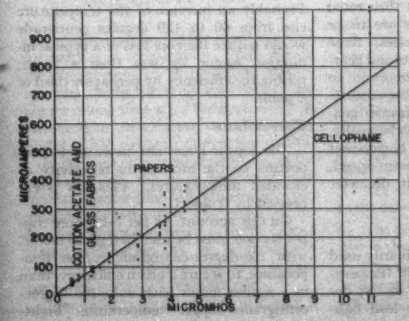

Figure 9. Comparison of corrosion current with conductivity of water extract for fabrics, paper, and cellophane

Corrosion current is in microamperes per mil thickness for a humidity of 100 per cent plus dew at 35 degrees centigrade. Conductivity of water extract is in micromhos per centimeter per mil thickness for 100 square inches per liter of water

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2. Causes of Corrosion of Fine Copper Wire Carrying a Potential, H. N. Stephens, G. B. Gehrenbeck. AIEE Transactions, volume 59, 1940, June section, pages 357–60.

Rating of High-Temperature Induction Motors

P. L. ALGER
FELLOW AIEE

H. A. JONES
NONMEMBER AIEE

Synopsis: The advent of new high-temperature insulating materials, such as the silicones, gives new freedoms to the motor designer. It is probable, however, that factors other than insulation will limit the desirable motor-temperature rise to values well below the endurance limits of these materials. It is, therefore, desirable to recognize that the size of an induction motor is measured electrically by its breakdown torque, and mechanically by the size of shaft and bearings, the temperature rise being only a secondary factor. Calculations are presented, based on idealized assumptions, which indicate that the optimum temperature rise for continuous rated induction motors is below 80 degrees centigrade, whatever the insulating materials used.

SOME NEW synthetic insulating materials, such as the silicones, have much higher temperature endurance than any flexible insulations heretofore known. It is probable that coil windings insulated with these new materials will have fully as long a useful life at a continuous temperature of 175 to 200 degrees centigrade as present class *A* or class *B* insulations have at their standard hot-spot temperature limits of 105 and 130 degrees centigrade, respectively. Presumably AIEE Standard 1[1] will be revised, to recognize these new materials, with a permitted temperature rise by resistance of the order of 120 degrees centigrade; on the same basis as the 60- and 80-degree-centigrade rise values now recognized for class *A* and class *B* materials.

These materials will open the way to smaller and lighter motors for many special applications, where intermittent operation, frequent starting, or restricted ventilation make small frames and high temperatures necessary. Also, they will have an insurance value because they will enable motors to withstand stalling and exposure to high ambient temperatures for longer periods. The silicones, therefore, will be welcomed by motor designers.

It is well known, however, that a large proportion of the general-purpose motors now produced in a highly competitive market have temperatures well below those permitted by the present rules.[2] Also, despite the availability of class *B* insulations, the lower temperature class *A* insulation is used for most low-cost electric apparatus.

It, therefore, appears that the high temperatures permitted by the new materials will not be utilized in many applications, even when the materials themselves are employed.

Two questions, therefore, arise:

1. What is the optimum temperature rise for general-purpose electric equipment, such as an induction motor, for example?

2. How should the method of rating be changed, if the operating temperature is not limited by insulation life?

Effects of High Temperatures

There are several ways in which temperature affects the operation of a motor, besides the thermal life of the insulation.

Bearings

The organic bearing lubricants deteriorate rapidly at temperatures above 80 to 90 degrees centigrade. A very rough rule for general-purpose induction motors is that the temperature rise of the bearings is half that of the windings. With a 40-degree-centigrade ambient temperature, therefore, a higher continuous temperature rise of the winding than 80 degrees centigrade generally will require special provisions for cooling the bearings. There is hope, however, that synthetic lubricants will be developed to withstand much higher temperatures.

It should be noted also that motors must have shafts and bearing diameters suited to the torques, pulley sizes, and belt pulls required to transmit their rated horsepower loads. If motors are to be built in radically smaller sizes, these smaller motors must have shafts and bearings materially larger in proportion to their frame diameters than now customary. Hence, existing motor frames generally must be redesigned mechanically, if they are to carry higher horsepower ratings. For a given horsepower, speed, and type of drive, the shaft diameter should be the same.

Metallurgy

A number of the metals ordinarily used in motors are affected by high temperatures. Pure tin solder melts at 232 degrees centigrade, and the tin–lead babbitts and solders soften at temperatures of the order of 150 degrees centigrade. The highest practicable temperature for soldering binding wire without affecting its strength is about 300 degrees centigrade. The hardened steel races of ball bearings gradually soften if kept at temperatures of 200 degrees centigrade or more. Pure copper under stress is subject to brittle fracture at temperatures above 160 degrees centigrade. However, by using silver solder, silver bearing copper, bronze or silver bearing alloys, and other special features, these temperature limits can be raised, if there is sufficient economic incentive.

Thermal Expansion

Thermal expansion occurs in differing amounts for copper, iron, and insulating materials. The higher the temperature, and the larger the machine, the greater is the risk of insulation cracking, and other types of mechanical failure. This factor is limiting in such large machines as turbine alternators, with temperature-rise values below 100 degrees centigrade, but is not important in small motors. Its importance when the new synthetic insulations are used will be measured inversely by the flexibility of these insulations. This still is being investigated.

Table I

Temperature Rise Above a 40-Degree-Centigrade Ambient Temperature	Relative Resistance of Copper
0	0.82
60	1.00
120	1.18
180	1.36
240	1.54

Iron Loss

The core losses are slightly reduced at increased temperatures because of the increased resistivity of the iron, and consequently lowered eddy currents. This factor is not important, however, as the iron loss itself is not controlling, and the eddy current loss is only a part of this. Probably an increase of the temperature rise from 60 to 120 degrees centigrade would reduce the core loss of a typical induction motor by less than a tenth; raising the efficiency by perhaps a third of a point.

Copper Loss

The copper losses are increased in proportion to the increase in resistivity at elevated temperatures. This law is expressed by Table I.

On this account, 18 per cent more copper section must be used in a given motor, with 160-degree-centigrade copper temperature, to secure a given efficiency, than in a similar motor with only 100-degree-centigrade copper temperature. Eight-

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P. L. Alger is staff assistant to the vice-president in charge of design engineering, General Electric Company, Schenectady, N. Y., and H. A. Jones does appliance project engineering for the General Electric Company, Bridgeport, Conn.

cen per cent of the full-load copper loss represents between one and one and one-half points in efficiency for a general-purpose induction motor, or rather more than ten per cent of the total losses.

Overload Capacity

The overload capacity of the motor is markedly reduced, when the full-load temperature rise is increased. Assume, for example, that two similar motors in a 40-degree-centigrade ambient temperature are compared at 1.25 times rated load, motor *A* having 60 degrees centigrade, and motor *B*, 120-degree-centigrade rise at rated load; both motors having the same component losses at rated load. In each case, the copper losses at 1.25 load will be roughly 1.56 times the copper losses at rated load, since they vary as the square of the current.

Since the temperature rise at overloads is nearly proportional to the copper loss, motor *A* will have an apparent temperature rise at 1.25 load of about 1.56×60, or 94 degrees centigrade, while *B* will have about 1.56×120, or 188 degrees centigrade rise. With these increases in temperature, the copper resistance increases also, causing higher losses and still further rise of temperature. This causes the phenomenon of "temperature creep," whereby the temperature goes on increasing for a long time after the application of an overload, in extreme cases becoming unstable and rising to destructive values.

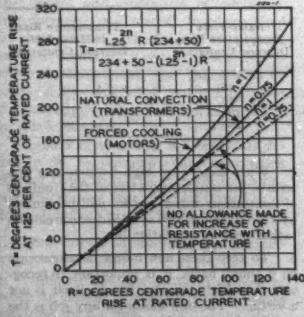

Figure 1. 125-per-cent versus 100-per-cent current temperature rise for electric apparatus with an ambient temperature of 50 degrees centigrade

Temperature rise assumed proportional to the *n*th power of the I^2R loss

In the case of natural convection, as for a transformer, the heat dissipation rate increases faster than the temperature rise, so partially offsetting the effect of increased copper resistivity. In the case of forced convection, as for a high-speed motor, the heat-dissipation rate is proportional to the temperature rise.

These effects are illustrated in Figure 1, from which the net additional temperature at 1.25 load can be estimated as a function of the rise at rated load. It is interesting to note also that the thermal time constant of the motor with 120-degree-centigrade rise is 16 per cent greater on overloads than that of the motor with 60-degree-centigrade rise, due to this temperature-creep effect.

All of the effects discussed under previous headings are produced by the extra temperature rise on overload, their magnitudes increasing rapidly as the rated-load temperature rise is increased.

It is a general rule that the life of organic insulation is halved for each ten-degree-centigrade rise in temperature, approximately. The effects of temperature on lubricants, expansion, and so forth, also increase exponentially. Therefore, even if the materials in motor *B* have the same life at 160 degrees centigrade as those in motor *A* have at 100 degrees centigrade, it is probable that motor *B* will have a life at its ultimate 1.25 load temperature of 285 degrees centigrade (Figure 1) only a small fraction of the life of motor *A* at its 1.25 load temperature of 147 degrees centigrade (Figure 1).

If the ten-degree-centigrade law for half life holds for the insulating materials in motor *A*, they will last only about four per cent of the time at 1.25 load that they would last at rated load. Even if the materials in motor *B* are so much more heat resistant that they follow a 15-degree-centigrade law for half life, this motor will still last only one-third per cent as long at 1.25 load as at rated load. Other estimates of the life at one and one-fourth load for different full-load temperature rises are given in Table II.

Thus, the magnitude and duration of overloads must be considered very carefully before a high temperature rise is selected for electric equipment.

Selection of Optimum Temperature

The urge to use a higher temperature is, of course, the advantage gained in reduced size, weight, or cost. There must be some optimum temperature rise, therefore, which strikes a balance between these advantages and the disadvantages mentioned above.

A series of calculations were made to determine this optimum temperature rise for a general-purpose induction motor of about 30-horsepower rating. These calculations were based upon several assumptions, as follows:

1. The ratio of motor length to diameter was held constant.
2. The over-all weight of the motor varied as the cube of the diameter.
3. The air-gap length varied as the square root of the motor diameter.
4. The maximum torque of the motor was held constant, which in turn signified that the motor reactance remained at one value.
5. The flux densities of the stator teeth and core were held at a specified constant value.
6. The core loss and windage and friction were held constant.
7. The space factor of the stator slots was held constant until the 60-degree-centigrade temperature-rise point was reached. At this rise, the space factor changed as a result of changing from class *A* to present class *B* insulating materials.
8. The temperature rise of the motor was assumed to be directly proportional to the heating losses, and inversely proportional to the square of the motor diameter.
9. With the motor running continuously at name-plate temperature rise, the motor life was taken to be seven years. In order to evaluate the overload life of the motor, the following duty cycle was assumed:

Two hours per day at three-fourths load
Four hours per day at full load
Two hours per day at one and one-fourth load

In addition, it was assumed that the temperature rise necessary to halve insulation life became greater as the name-plate rise increased, as given in Table III.

With the assumptions of a duty cycle and the temperature rise necessary to halve insulation life, it was possible to evaluate a motor-replacement cost. This cost of re-

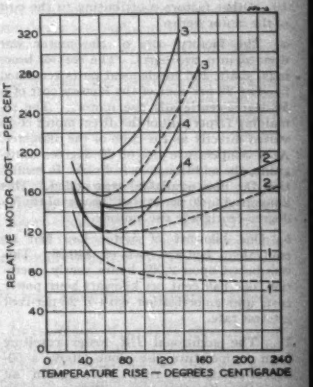

Figure 2. Effect of rated-load temperature rise on motor cost for 30-horsepower induction motor

Solid curves give costs with insulation allowances now in use. Dotted extensions show cost with allowances and insulation costs equivalent to class *A*

The break in the solid curves is a result of changing from class *A* to class *B* insulation costs and allowances

Curve 1—Direct factory cost of motor
Curve 2—Factory cost plus efficiency cost
Curve 3—Factory plus efficiency plus replacement cost
Curve 4—Factory plus efficiency plus additional fan cost

Table II Reduction in Motor Life on Overload

Temperature Rise From Figure 1		Ratio of Life at 125-Per-Cent Current to Life at Rated Current	
At Rated Current, Degrees Centigrade	At 1.25 Current, Degrees Centigrade	Life Halved for Each Ten-Degree-Centigrade Temperature Increase	Life Halved for Each 15-Degree-Centigrade Temperature Increase
40	68	0.14	0.26
60	107	0.038	0.114
80	149	0.0083	0.041
100	194	0.0015	0.013
120	245	0.00017	0.0031
140	305	0.00001	0.0005

placing worn-out motors indefinitely was amortized at a ten-per-cent interest rate.

10. Other factors contributing to the cost of the motor were:

a. The factory cost of the motor was divided into two parts. The cost of bearings, shaft, and mechanical parts remained fixed at 25 per cent of the factory cost of a 50-degree-centigrade rise motor. The remaining 75 per cent of the direct motor costs varied directly as the cube of the diameter. At a temperature rise of 60 degrees centigrade, the additional cost of class *B* insulation (as now available) was added. This amounted to 20 per cent of the cost of the 50-degree-centigrade rise motor.

b. One kilowatt of motor loss had an equivalent factory cost of $40.00. This was based upon 2,000 hours yearly operation, one-half cent per kilowatt hour power cost, and amortization with a 25-per-cent interest rate.

11. The additional I^2R losses resulting from temperature rise alone (above a 50-degree-centigrade rise) were given an equivalent factory cost, and this amount was spent on extra ventilating equipment. The cost of fans for the 50-degree-centigrade rise motor was taken as five per cent of the direct factory cost. The heat dissipation varied as the fourth root of the amount spent on fans.

Figure 2 shows results obtained based upon the foregoing assumptions. The solid curves indicate the effects of going to higher-temperature motors with present-day insulation costs and space allowances. The distinct break at 60-degree-centigrade rise is caused by the additional cost of installing class *B* insulating materials, and the additional insulation-space allowance which must be made in the stator slots. The dotted extensions above 60 degrees centigrade indicate characteristics that could be obtained if, in the future, the cost and space allowance for class *B* materials could be brought down to present-day class *A* standards.

It will be noted that curve 2, showing the cost of the bare motor plus losses, has a minimum at 80-degree-centigrade rated-temperature rise, even though the motor is assumed to operate only 2,000 hours a year.

If additional cooling is provided, as indicated by curve 4, to increase the overload capacity, the minimum cost occurs at a little lower temperature, and this effect would be accentuated if the motor were operated for more than 2,000 hours.

Curve 3, which adds the replacement costs on the basis of continuous operation throughout the year, 25 per cent of the time at 1.25 load, shows a further reduction of the temperature rise for minimum cost. The significance of this curve lies in its shape rather than the actual values, since it is based on quite arbitrary assumptions.

Discussion

The foregoing indicates that although there is no single answer to the question, the optimum general-purpose motor temperature rise at rated load is below 80 degrees centigrade by resistance.

One point that stands out in the above analysis is that the space required for the insulation is of great importance. For example, glass fiber and varnish-insulated wire, as used in class *B* insulated induction motors, has roughly ten-per-cent larger diameter than resin-insulated wire, as now commonly used in class *A* motors, requiring an increase of roughly one half a frame size, or about 15 per cent in equivalent rating, for the same motor performance.

A second point that stands out from the analysis is the importance of efficiency in the case of motors operating for extended periods. As the curves in Figure 2 illustrate, even if a motor is designed for a high-temperature rise, it may be economical to provide extra cooling simply because of the reduced losses and greater overload capacity thereby obtained at a relatively low cost.

It seems clear, therefore, that the temperature rise of continuous rated motors will continue to be a useful measure of their performance, and that the present usual values will not be changed materially by the advent of the new high-temperature insulations.

For the short-time-rated and intermittent-duty motors, where the temperature often has been limiting, the temperature rise will become less important, and the breakdown torque of the motor will assume a greater importance as a measure of motor size.

There are, therefore, three distinct measures of motor capacity:

1. The breakdown torque.
2. The shaft and bearing sizes.
3. The rated-load temperature rise (inverse).

All of these must be chosen to suit the application. In a particular case, any one of these may be limiting.

Conclusions

The following conclusions are reached from this analysis:

1. The silicones and other new high-temperature insulating materials will give new freedom to the motor designer, permitting lighter weights, more severe duty cycles, and more difficult applications of motors in many cases.

Table III

Name-Plate Temperature Rise, Degrees Centigrade	Temperature Rise to Halve Life, Degrees Centigrade
50	10
60	12
100	15
200	20

2. With these new high-temperature materials, the temperature rise of the windings of continuous rated motors will be limited by the efficiency and overload requirements rather than by insulation life.

3. To keep these new motor developments on a sound basis, it is important to recognize that high temperature in itself is not a virtue. The best motor for any job is the one that has the right combination of breakdown torque, efficiency, and shaft size, with the lowest temperature rise that can be secured at a reasonable cost.

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Arc-Backs in Rectifier Circuits
Artificial Arc-Back Tests

R. D. EVANS
FELLOW AIEE

A. J. MASLIN
ASSOCIATE AIEE

THE enormous development in the use of rectifiers for the electrolytic reduction of light metals has been an outstanding development of World War II. One important problem in this rectifier development has been the performance at the time of rectifier arc-back. Currents of between 50,000 to 100,000 amperes may be encountered on an individual rectifier and associated transformer. Still higher currents would obtain if back feed from other units on the same bus were not eliminated by prompt isolation from the circuit or d-c bus.

This development in rectifiers has presented the need for more basic information on the performance of rectifier circuits under arc-back conditions. Knowledge of arc-back currents is important in the design and operation of rectifiers, transformers, and circuit breakers used for their control. The scope of the present paper is limited to a general discussion of arc-back phenomena and the results of artificial arc-back tests, particularly as to the magnitude–time characteristics of the arc-back currents.

Arc-back of a rectifier is a term that refers to the phenomena that occur when current flows from the cathode to an anode, the reverse from normal direction of flow. In effect, an arc-back provides

1. Short circuit on one phase of a rectifier-transformer circuit.

2. Paths for the flow of direct current or pulsating current from other rectifier phases and from the d-c bus.

Consequently, the arc-back currents under these conditions are greater than the sustained currents corresponding to a three-phase short circuit on the rectifier-transformer secondaries of the star group subjected to arc-back.

Arc-back phenomena contain many factors that are as yet but imperfectly understood. Commercial rectifiers are subject to occasional arc-backs, the frequency of which is known to increase as functions of the rectifier current and output voltage. The tendency to arc-back is also known to increase as the amount of phase control is increased. It is common experience that the frequency of arc-back decreases after a unit becomes "seasoned." The frequency of arc-back also increases if severe loads are applied on a cold rectifier or one that has been carrying a very light load. These factors have been recited as a matter of general background because the mechanism of arc-back was not within the scope of the present investigation.

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R. D. EVANS is consulting transmission engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and A. J. MASLIN is design engineer in the transformer engineering department of the same company at Sharon, Pa.

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Artificial Arc-Back Tests

In studying the character of arc-back phenomena,[1,2] the most desirable method, of course, is to observe actual arc-backs under service conditions. Records of arc-backs that have occurred under service conditions have been obtained by means of an instrument especially devised for this purpose, called the memnoscope.[3] This investigation, however, did not make use of that method because it was undesirable to take all the necessary recording apparatus to the field and because it was undesirable to await arc-backs as they occur in practice. For this reason the investigation was made in the laboratory with some field tests for corroboration of the chief results.

There are two principal methods for the artificial representation of arc-back phenomena, namely,

1. Short-circuiting switches.

2. Reverse-connected ignitrons or single-tube rectifiers.

The simplest method of simulating an arc-back is to connect the anode to the cathode by a short-circuiting switch. In particular, the short-circuiting switch was provided with a high-speed mechanism which was electronically controlled so as to initiate the arc-back close to the desired point of the voltage wave.

The second method of simulating arc-backs is to use a reverse-connected rectifier in parallel with the ignitron or other rectifier element to be subjected to an artificial arc-back. In practice a reversed ignitron was used and it provided an easy method for controlling the initiation of the artificial arc-back. However, the reversed ignitron presents some important differences from the actual ignitron subjected to arc-back. In the actual arc-back, current flows from the cathode to the anode, whereas in the reversed ignitron it flows from the anode to the cathode. Another difference is that a loaded ignitron subjected to actual arc-back is operating at normal temperatures and has normal ionization, whereas the reversed ignitron is initiated from a no-load condition. However, the test data, subsequently given under the heading of "Arc-Drop Characteristics of Arc-Back Currents," show that for the same current flow there is little actual difference in the arc drop of a reverse-connected ignitron from that of a normally connected ignitron under arc-back conditions.

In comparison of the two methods of representation of an arc-back, it will be evident that the short-circuiting switch offers too small a resistance because the effect of the arc drop in the ignitron is not taken into account. Compensation for this arc drop might be approximated by the addition of a resistance in series with the short-circuiting switch. However, the simplicity of the scheme using a short-circuiting switch commends itself, and the resulting slightly pessimistic test condition is not objectionable.

Factors Affecting Arc-Back Current

In the study of arc-back currents, it is convenient to refer to the schematic diagrams of rectifier circuits that are illustrated in Figure 1. In the two parts of this figure are shown the two principal methods used for clearing arc-backs.

The principal factors that affect the arc-back current magnitudes for either the initial or subsequent peaks are as follows:

1. Characteristics of the a-c supply system, including the reactance of the rectifier transformer and source.

2. Characteristics of the d-c back-feed system, including the breakers used to interrupt back-feed current.

3. Method of clearing arc-backs.

4. Arc-drop characteristics of arc-back currents.

5. Rectifier firing conditions, including the use of phase control.

6. The time of initiation of the arc-back.

7. Sympathetic arc-backs in associated rectifier elements and their possible recovery for subsequent normal nonconducting periods.

1. Characteristics of A-C Supply System

The basic factors in the determination of arc-back current are, of course, the circuit voltage and the reactance of the rectifier transformer and the source. In most large rectifiers the size of the individual transformer is fairly definite, corresponding approximately to an output

of 10,000 amperes, or 6,000 kw at 600 volts. Such transformers are normally built on a three-phase core with two groups of windings, which operate substantially as independent units. Frequently each secondary winding supplies through a balance coil a second ignitron tube in parallel with the first, but for simplicity these are not shown. The equivalent impedance diagram for one of these transformers with each group having one three-phase primary winding and two three-phase secondary windings is shown in Figure 2. Examination will show that the two secondary windings of each group are very closely coupled. Because of the close coupling between the secondary windings, the equivalent-star diagram has a branch connected to the high-voltage terminal that constitutes most of the transformer reactance. In small systems supplying a single rectifier transformer, the source reactance may be quite appreciable in comparison to the transformer reactance. However, in the case of large rectifier stations the reactance of the source becomes small in comparison with the reactance of an individual transformer, so that the currents would be increased by only 5 to 15 per cent if there were an infinite bus at the high-voltage terminals.

An arc-back causes heavy direct currents to flow through the transformer-secondary windings, the effect of which is to saturate the core. However, because the arc-back is in effect a short circuit, the increased exciting currents that flow as a result of the saturation in the cores do not appreciably increase the total alternating current. This result is shown in an oscillogram included in the discussion of laboratory tests.

2. Characteristics of D-C Back-Feed System

Rectifiers may feed into load circuits supplied by motor generators, synchronous converters, or other rectifiers. However, in large stations, the characteristics of the d-c circuit are usually relatively unimportant in determining the magnitude of the back-feed current. This results from the circumstances

1. That the inductance of the back-feed system is high.

2. That high-speed anode or cathode breakers are used which are capable of isolating the arc-back before the back-feed currents reach large magnitudes.

The magnitude of back-feed current is usually limited in large rectifier stations to from 40,000 to 50,000 amperes, the amount varying somewhat with the point of initiation of the arc-back.

3. Method of Clearing Arc-Backs

Two methods for clearing of arc-backs are in common use; these are known as "cathode-breaker clearing" and "anode-breaker clearing"[4,5] and are illustrated schematically in Figure 1. This illustration applies to larger rectifier installations used in the electrochemical industry for which two rectifier sections are supplied from single transformers. With the system of Figure 1a the isolation of an arc-back in a rectifier element of one star group requires

1. The opening of the corresponding high-speed cathode breaker, normally operating in one-half cycle (on a 60-cycle basis).

2. The opening of the a-c supply breaker, normally operating in eight to ten cycles.

With the system of Figure 1b the isolation of an arc-back in a rectifier element of one star group requires the opening of the associated anode-breaker pole, operating in about one-half cycle. It will be observed that the arc-backs are isolated from the d-c bus by the cathode breaker in one case and by the anode breaker in the other, circumstances from which are derived the terms which designate the method of clearing. Of course, with cathode-breaker clearing, the opening of the a-c supply breaker is required to isolate the arc-back from the a-c supply. With anode-breaker clearing, the opening of the a-c breaker is not required for isolating the a-c supply; consequently, one a-c breaker may be used in the supply to several rectifier units. A semihigh-speed cathode breaker operating in two or three cycles is used for disconnecting the rectifier from the bus; it also serves as a backup for the anode breaker. In the anode-breaker scheme the individual poles may be operated separately and restored separately or operated as a group as a result of the operation of an individual pole. In the small rectifier installations each rectifier section is supplied from a separate transformer and cathode-breaker clearing has been the method generally employed. The principal difference between these two methods of clearing an arc-back is in the duration of the arc-back condition, which with (1) cathode-breaker clearing is one-half cycle for disconnecting the d-c back feed and eight to ten cycles for disconnecting the a-c feed,

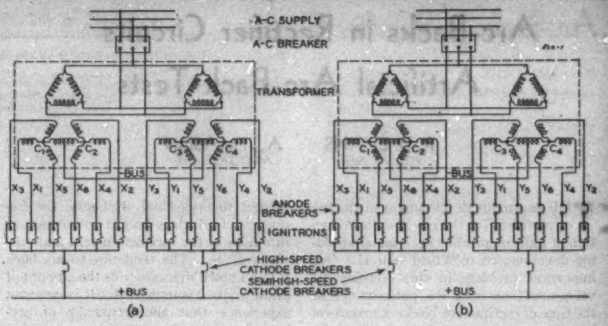


Figure 1. Schematic diagram illustrating the two principal methods of clearing rectifier arc-backs

(a). Cathode-breaker clearing
(b). Anode-breaker clearing

and (2) with anode-breaker clearing is one-half to two cycles.

4. Arc-Drop Characteristics Under Arc-Back Currents

Arc drop of a rectifier element, as is well known, increases as a function of the current carried. However, the magnitude of this voltage drop depends upon the particular design of the rectifier and upon the magnitude of the current. The arc-drop data shown in Figure 3 were taken from measurements on the ignitron tube, which is the most widely used unit in commercial service. Figure 3 shows arc-drop data obtained for several different conditions of current flow, including normal forward-flow current for the first and subsequent cycles of heavy current resulting from artificial arc-backs. Figure 3 also shows arc-back data obtained from some natural arc-backs which were the result of an artificial arc-back on some other anode. In general, the arc drops obtained under natural arc-backs have magnitudes corresponding closely to those

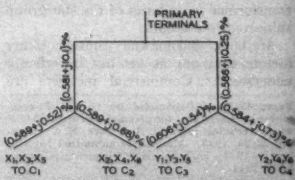


Figure 2. Equivalent impedance diagram for typical rectifier transformer used in large electrochemical installations

Diagram applies to transformer with double-delta primary and quadruple-wye secondary as in Figure 1. Impedances expressed in per cent on total transformer kilovolt-amperes

obtained for artificial arc-backs with a reverse-connected ignitron. The arc-drop data also do not show any important difference in the arc-drop magnitude for currents on the first cycle or for subsequent cycles for heavy current flow when compared on the basis of the same maximum current. It was somewhat surprising that the arc drop under arc-back conditions became so large in comparison with the normal full-load arc drop which is also shown in the figure.

The arc-drop data shown in Figure 3 would not permit drawing a simple curve to represent average performances. The data suggest

1. A slow increase in voltage drop for currents up to 20,000 amperes.

2. A rapid increase in the range between 20,000 and 40,000 amperes.

3. A reduced rate of increase for the range between 40,000 and 80,000 amperes, the maximum for which arc drop was observed during arc-back tests.

The presence of arc drop reduces considerably the magnitude of maximum arc-

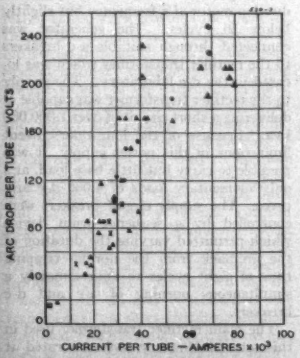


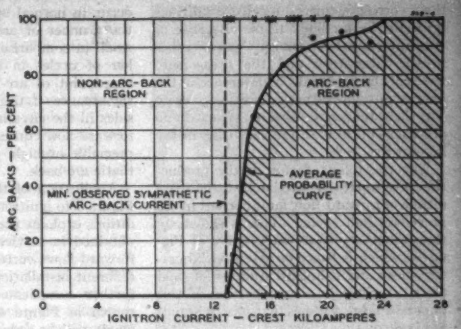
Figure 3. Arc-drop characteristics of standard ignitron tube under different conditions

Normal conduction, anode to cathode:
⊡—Arc drop under full-load conditions.
Reverse-connected ignitron in parallel with normal-connected unit:
▲—First cycle ▲—Subsequent cycles.
Reverse-connected ignitron in place of normal-connected unit:
⊙—First cycle ●—Subsequent cycles
Reverse conduction, cathode to anode:
x—Natural arc-back

back current. The difference between maximum arc-back currents on artificial arc-back tests with a reversed ignitron and on tests with a short-circuiting switch is about 15 per cent, and this may be attributed to the effect of additional arc drop in one phase. Because of the arc-drop characteristics under heavy currents, it is evident that arc-back simulation by means of a short-circuiting switch slightly increases the arc-back currents.

Figure 4. Probability of arc-back—plotted as a function of previous values of forward-flow fault current in crest amperes per tube

●—Average for laboratory tests, using 2,000-ampere steps Minimum arc-back current and maximum non-arc-back current observed for individual tubes, plotted on 100 per cent and 0 per cent probability lines, respectively:



x—Different tubes, laboratory tests o—Different tubes, field test

5. Rectifier Firing Conditions

The method and time of firing each rectifier element has an important effect on the magnitude–time characteristic of arc-back currents. The general effect of phase control is to reduce the magnitude of arc-back currents. In the continuously excited rectifiers without phase control each incoming anode starts carrying current as soon as the proper difference of potential is reached, that is, when a slight positive potential appears on the incoming anode. In rectifiers with phase control obtained by grid or igniter delay, the start of conduction is correspondingly delayed. If the supply to the grid or igniter circuit is not affected by the arc-back currents, the firing will normally take place at definite points on the a-c supply wave. In this investigation only ignitrons under normal firing conditions were investigated; tests in the laboratory were made without delayed firing or phase control; tests in the field were made under actual operating conditions and these included some phase delay.

6. Initiation of the Arc-Back

The magnitude of the initial crest of the arc-back current is importantly controlled by the time of initiation of the arc-back, this magnitude being the maximum when the arc-back follows immediately after the end of normal conduction and a minimum when the arc-back occurs just before the end of the nonconducting period. If the arc-back occurs shortly before normal conduction begins, there is a small first cycle followed by a high second cycle which approaches the magnitude of current corresponding to the crest of an arc-back occurring at the end of normal conduction. The magnitude of the initial arc-back current crest is of principal importance when anode breakers are used, since the subsequent arc-back current cycles are not experienced because of the isolation of the phase subjected to arc-back. With cathode-breaker clearing the back feed is quickly interrupted, but the current tends to reach the same crest at the end of eight or ten cycles, regardless of the point of initiation of the arc-back. There is, however, the difference that if the arc-back occurs late in the cycle there are fewer cycles of high current.

7. Sympathetic Arc-Backs

By a sympathetic arc-back is meant one which occurs as the result of a natural or artificial arc-back in another anode circuit. The causes of such sympathetic arc-backs are not fully known. However, the tendencies toward sympathetic arc-backs are importantly affected by the magnitude of the arc-back current and previous load conditions in the rectifier unit. If the arc-back tests are made under conditions approximating the severity of arc-back current encountered in the usual commercial operation, the arc-back current magnitudes can reach 50,000 to 70,000 amperes or even higher. Under these conditions the forward-flow current in units of the same star group as the anode subjected to arc-back become very large. In the laboratory tests subsequently described, efforts were made to load the ignitrons so as to approximate the temperatures and ionization condi-

Table I. Crest Values of Anode Currents in Field Tests

Test	Current Direction*	Kiloamperes in Various Anodes					
		X_1	X_2	X_3	X_4	X_5	X_6
1	F	48	36	41	20	0	39
	R	0	0	31	34	68	0
2	F	37	24	43	26	0	27
	R	0	0	0	0	67	0
3	F	35	21	41	25	0	26
	R	0	0	0	0	65	0
4	F	37	37	43	25	0	39
	R	0	0	0	40	62	0
5	F	36	22	44	26	0	27
	R	0	0	0	0	62	0

* F, forward flow, R, reverse flow on arc-back. Artificial arc-back placed on anode X_5.

tions corresponding to service conditions prior to the arc-back tests. Because of the differences between the "green" tubes in the laboratory and the "seasoned" tubes in the field and the difference in the operating-temperature conditions, there was less tendency toward sympathetic arc-backs on tests in the field than in the laboratory.

The controlling factor in the production of sympathetic arc-backs is the magnitude of forward-flow fault current in the preceding half cycle.[6] This is shown by the probability-of-arc-back curve of Figure 4, which is based on extensive laboratory tests and a limited number of field tests described in a later section of this paper. Figure 4 shows that for the standard ignitron tube there are

1. A non-arc-back region (or more precisely, a low-arc-back region) for forward-flow currents of less than 13,000 amperes crest.

2. An arc-back region for forward-flow currents greater than 24,000 amperes crest.

3. An intermediate region for which sympathetic arc-backs occur with high probability.

For this intermediate region an average probability curve is plotted from the results of tests using relatively narrow current ranges. Also on Figure 4 are plotted for individual tubes, whenever justified by the data,

1. The highest forward-flow current without arc-back.

2. The lowest forward-flow current with arc-back.

Figure 4 is based on 100 artificial arc-back tests in the laboratory and each test may provide data on 5 or 11 ignitron tubes. It will be observed that the results from the five field tests are not inconsistent with data obtained from the extensive laboratory tests.

In connection with Figure 4, it may be observed that the probability curve should show a definite but negligibly small value for low currents, since arc-backs do occur in normal operation, even though the number of arc-backs is exceedingly small in comparison with the total number of cycles in operation. From the standpoint of arc-back phenomena, the significance of the probability curve resides in the circumstance of whether the forward-flow current will result in an appreciable or high probability of sympathetic arc-back.

Application of the rectifier data from Figure 4 to ignitrons under arc-back conditions explains the wide range of results obtained in service. The magnitude of forward-flow current varies widely in different installations and the results are further complicated by probability, as shown in Figure 4. In some cases no anode will be subjected to sympathetic arc-back. In other cases, all anodes will be subjected to sympathetic arc-backs so that the anode-current records look like those of polyphase short circuits. An anode subjected to a sympathetic arc-back for several cycles may recover its normal characteristics as a rectifier and may even subsequently develop a second sympathetic arc-back. Oscillograms of various conditions will be shown later in connection with the discussion of artificial arc-back tests in the laboratory and in the field.

The presence of sympathetic arc-backs has an important bearing on the arc-back phenomena in general. The presence of sympathetic arc-backs tends to reduce the maximum current to be carried by the ignitron unit or the particular transformer winding associated with the initial arc-back. If the second arc-back occurs on the other winding on the same core with the winding supplying the rectifier unit initially subjected to arc-back, the sum of the two anode currents approaches approximately the original value. From an examination of Figure 2, it will become apparent that when both windings are short-circuited, the total short-circuit current will be about the same as for a short circuit on one winding, with the current divided between the two secondary windings. When anode breakers are used, sympathetic arc-backs may increase the number of poles operated and the time required completely to isolate the arc-backs, since the second arc-back must be cleared by a second breaker operation, a process that may be repeated in sequence.

Artificial Arc-Back Tests in the Laboratory

The characteristics of the particular ignitron tube have an important effect on arc-back phenomena, since these determine the actual arc drop and the tendency to produce sympathetic arc-backs. All arc-back tests referred to in this paper were made on the standard ignitron tube, which is used widely, particularly in the larger electrochemical installations.

An extensive series of artificial arc-back tests was made in the laboratory on the setup illustrated in Figure 5. The power supply for these arc-back tests was obtained from the number 2 high-power laboratory. The high-power-laboratory generator was driven by an induction motor at a frequency but slightly below 60 cycles. The generator was connected through suitable a-c breakers to the rectifier transformer which was located in the d-c laboratory. The supply to the rectifier transformer was capable of delivering a short circuit of over 1,000,000 kva. Because of the long-time-current limitations in this power supply, it was possible to carry but little base load, and only momentary loads of 4,000 d-c amperes. The supply circuit breakers were controlled by a sequence-drum device which permitted varying the duration of the arc-back from the normal tripping time of eight cycles to approximately a simultaneous opening of a-c and d-c breakers.

The main rectifier transformer used in this set of laboratory tests was rated at 8,500 kva and provided with double delta-primary windings for 13,800 volts with quadruple-wye secondaries of 712 volts from line-to-neutral terminals, and with interphase transformers. This main power transformer was designed to deliver 780-volt d-c service when used with two sets of ignitron tubes, each set delivering 5,000 amperes continuously. This transformer employs a core constructed of Hipersil, the new high-permeability core material. It has the same weight and physical dimensions, and substantially the same losses, as the older 6,550-kva transformer mentioned later in the discussion of field tests. The core-and-coil assembly, after the completion of the laboratory arc-back test program, is shown in Figure 6. This transformer was designed to withstand the stresses attending arc-back currents of 100,000 amperes, thus the laboratory tests furnished an experimental verification of the design.

Two rectifier frames, each with six ig-

Table II. Magnitude of Arc-Back Currents

Arc-Back Simulation	Laboratory Test, 8,500-Kva Transformer; Primary, Double-Delta; Secondary, Quadruple-Wye With Interphase Transformers		Field Test, 6,550-Kva Transformer; Primary, Double-Delta; Secondary, Quadruple-Wye With Interphase Transformers	Laboratory Test, 250-Kva Transformer; Primary, Delta; Secondary, Double-Wye With Interphase Transformers
	Reversed Ignitron	Short-Circuiting Switch	Short-Circuiting Switch	Short-Circuiting Switch
I_{AB}—Maximum arc-back current (amperes)	81,500	95,000	67,800	12,500
*I_{BP}—Back-feed current (amperes)	25,000	25,000	22,000	2,500
E_B/X—Symmetrical short-circuit current (crest amperes)	52,000	52,000	38,000	8,000
$\frac{I_{AB}}{E_B/X}$	1.59	1.83	1.78	1.56
$\frac{I_{AB}-I_{BP}}{E_B/X}$	1.1	1.35	1.21	1.25

*I_{BP}—This is the current fed out the neutral point of the star group subjected to arc-back; it includes current from the other star groups of the same or other transformers.

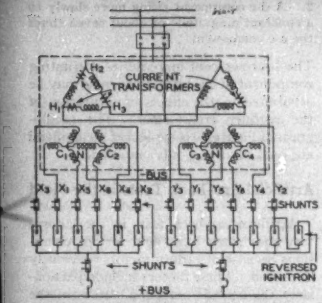


Figure 5. Schematic diagram for artificial arc-back tests on a large rectifier installation

Arc-back on phase Y_2 with simulation by reversed ignitron in parallel with normally connected unit. In many tests the reversed ignitron was replaced by a short-circuiting switch. Locations of shunts and current transformers for oscillograph measurements are shown

nitron tubes, were provided for the tests. In addition, a single tube was provided to initiate an artificial arc-back in some tests. Special auxiliary transformers were used for the supply of the excitation circuits. Reactor-firing circuits were provided for the two six-tube frames. A phase-shifting transformer was used for the control of the tube which was used to simulate an arc-back. Two high-speed d-c breakers, which trip in approximately one-half cycle on heavy reverse current, were provided. The laboratory motor generator sets, including four 1,500-kw 750-volt d-c generators, were connected through high-speed breakers to the d-c busses of the X and Y sections of the transformer. A short-circuiting breaker, equipped with electronic control, was also used in many tests for simulating an arc-back. Anode breakers were used in the leads of the X section of the transformer during some tests.

Figure 7 shows an interesting record obtained during the laboratory tests with the setup just described. This test gave the highest arc-back current obtained with a reverse-connected ignitron and the amount was 81,500 amperes. It will be noted that during this particular test the application of an artificial arc-back on anode circuit Y_2* caused every ignitron on the other phases to arc-back until the circuit was opened by the a-c supply breakers. The X-section anode-current records (not shown) included a single loop of current, the current flow being limited by the operation of the high-speed cathode breaker. It will be noted that the current flow corresponds to a three-phase short circuit on the secondaries of the transformer for the Y section. The back feed to the Y section represented a maximum of 36,500 amperes and had a maximum rate of rise of 5,270,000 amperes per second.

With the same setup but with the reverse-connected ignitron replaced by a short-circuiting switch and with the arc-back being initiated at the end of the normal-conducting period, a maximum arc-back current of 95,000 amperes was recorded.

The oscillogram of Figure 8 is of particular interest. This test was made with the two sets of ignitron tubes connected to the X group, leaving the Y group of the transformer disconnected. In this case an artificial arc-back with simulation by a short-circuiting switch was placed on anode X_3 and was initiated close to the end of normal-conduction period. In this test the ignitrons of the star group consisting of anodes X_2, X_4, and X_6 were not subjected to sympathetic arc-backs. However, the ignitrons for anodes X_1 and X_3 arced back for four cycles. On the fifth cycle all anodes recovered leaving only the single arc-back on anode X_3, the one subjected to artificial arc-back. It is of interest that the maximum arc-back current for anode X_3 has a first-cycle crest magnitude of 76,700 amperes and about equal magnitude on the fifth cycle. On the following cycle the ignitrons for anodes X_1 and X_3 were subject to sympathetic arc-backs and did not recover again until the primary circuit was interrupted. The primary current on phase C of the X section, the delta winding associated on the same core with the secondary winding for anode X_3, shows an almost fully displaced a-c wave which was quickly reduced in magnitude because of sympathetic arc-backs. However, on the cycle corresponding to the recovery from arc-back conditions of all anode circuits, the primary-current crest reaches a crest about equal to the initial crest.

With the test setup corresponding with that of Figure 8 but with anode breakers connected in the leads to X section, oscillograms of Figure 9 were obtained. In this case also, arc-back simulation was by a short-circuiting switch and the arc-back was initiated at the end of the normal-conducting period. The artificial arc-back was impressed on the circuit of anode X_5. Current flow is shown for anodes X_1, X_3, and X_4. In this case anode X_1 arced back at the end of its normal-conducting period and this necessitated the opening of the anode breaker for phase X_1 as well as for phase X_3, the phase subjected to artificial arc-back. On other tests with anode breakers the number of sympathetic arc-backs varied, involving in some cases a maximum of five phases. The first-cycle maximum anode current for any of the tests with anode breakers was 66,000 amperes, a value that is appreciably below the maximum crest obtained without the anode breakers. The difference may be explained in part by the fact that high-speed cathode breakers were used as well as anode breakers, and that both of these breakers were capable of introducing important arc drop within a half cycle from the inception of the artificial arc-back. Consequently, the actual arc-back current crest was appreciably reduced when high-speed cathode breakers were used with anode breakers. It has been estimated for this case that if semihigh-speed cathode breakers were used, the first-cycle crest would have amounted to about 70,000 amperes.

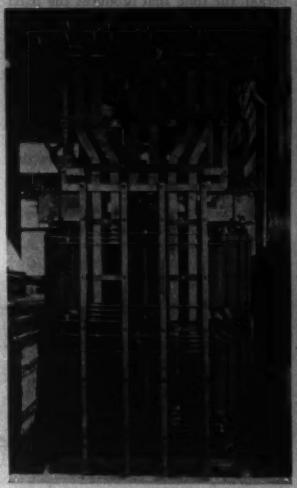


Figure 6. Core and coil assembly of 8,500-kva transformer as it appeared after detanking at the end of the laboratory tests

In another series of tests, six ignitron tubes were supplied from a bank of 250-kva transformers arranged in the usual double-wye secondary with interphase connection to produce 250 volts direct current. The rectifiers were adjusted to carry an initial load of 900 amperes and were fed into a d-c system consisting of a large motor generator set. The artificial arc-backs were applied by means of a short-circuiting switch; the arc-backs were isolated by the operation of a high-speed cathode breaker and by operation of the a-c supply breaker.

Oscillograph measurements during the artificial arc-back tests included the six anode currents obtained from shunts and the three primary-delta currents obtained from especially designed current transformers. A typical oscillogram of artificial arc-back is shown in Figure 10. In this test the artificial arc-back was placed on anode 5 and was initiated substantially at the end of the normal conducting

* Note that in Figures 7, 8, and 9 the anodes are designated as 5-Y instead of Y_5 and so on, as used elsewhere in text.

period, the time that produces the maximum first cycle of anode current, which reached a value of 12,200 amperes. This initial current was slightly reduced by disconnection of the back feed, and this slightly reduced value was maintained substantially constant on successive peaks throughout the arc-back condition which lasted for about 11 cycles. Examination of the other anode currents shows that they were also substantially constant throughout the arc-back conditions. The primary currents, however, show a considerable reduction in the d-c component. The alternating component of the primary current increases but slightly during the arc-back condition. The envelope of the primary current of phase *C* has been drawn in on the oscillogram and it shows the difference between the alternating components corresponding to 1,380 amperes at the beginning of the second cycle and to 1,430 amperes at the end of the arc-back condition. Analysis for phase *C* shows that the resultant magnetization (in ampere turns) is composed of

1. An a-c component reaching a substantially constant value in a few cycles.

2. A d-c component rising more slowly to a constant magnitude of about seven times the a-c component.

The four-per-cent increase in alternating component of the primary current may be attributed to the effects of saturation of the rectifier transformer. The oscillogram of Figure 10 is typical of an artificial arc-back involving only one anode.

Artificial Arc-Back Tests in the Field

Artificial arc-back tests in the laboratory may vary from field service conditions because of various factors previously discussed. These factors include particularly the use of "seasoned" tubes in the field which have normal operating temperatures and normal ionization prior to the arc-back. Accordingly, it was arranged to make a series of artificial arc-back tests at the Velasco, Tex. plant of the Dow Magnesium Corporation. The particular rectifier station used contains 12 ignitron-type rectifier sections supplied from six transformers with quadruple wye-connected secondaries. These six transformers are arranged to provide a 36-phase rectifier station which is accom-

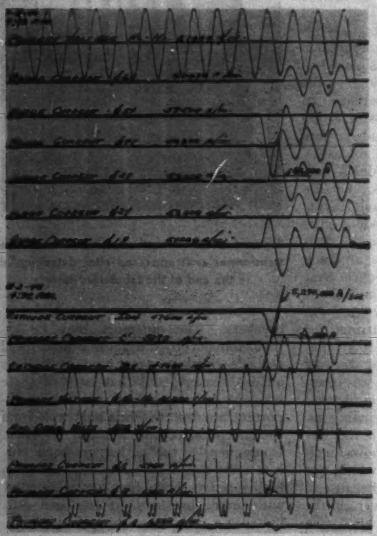


Figure 7 (left). Oscillogram of artificial arc-back tests in the laboratory

Simulation by reversed ignitron on anode Y_4, similar to Figure 5. Sympathetic arc-backs occur on all anodes of the *Y* group. Cathode-breaker clearing

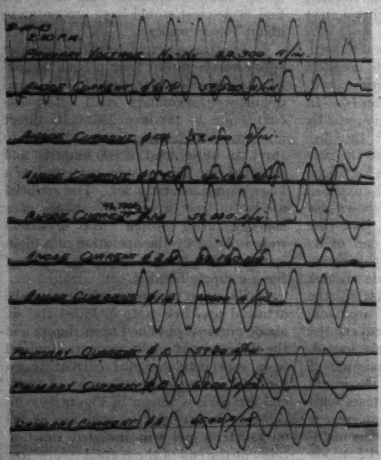
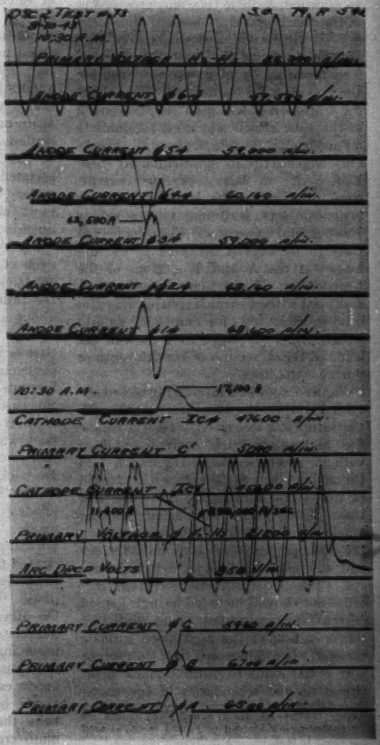


Figure 8 (lower left). Oscillogram of artificial arc-back tests in the laboratory

Simulation by short-circuiting switch. Test setup similar to Figure 5, except *Y*-section ignitrons placed in parallel with the *X*-section units. Sympathetic arc-backs occur in all ignitrons of the *X* group, and all recover on the fifth cycle and then reoccur. Cathode-breaker clearing

Figure 9 (right). Oscillogram of artificial arc-back tests in the laboratory

Simulation by short-circuiting switch. Setup identical with that of Figure 8, except anode-breaker clearing



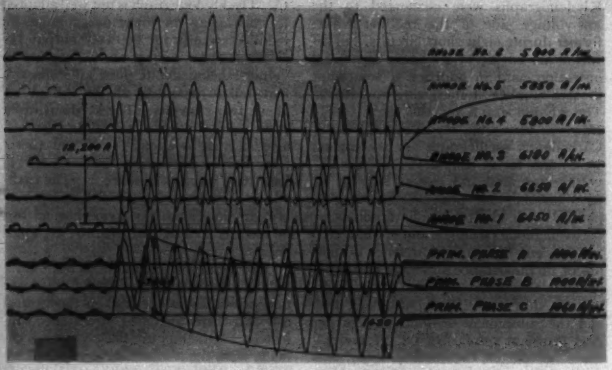


Figure 10. Oscillogram of artificial arc-back tests in the laboratory

Simulation by short-circuiting switch. Cathode-breaker clearing. Typical oscillogram of artificial arc-back tests without sympathetic arc-backs. (Certain lines retouched)

plished by using three delta-primary transformers and three wye-primary transformers and using four phase-shifting transformers. The tests were made on the transformer with delta primary that is connected to the source without phase-shifting transformer.

The artificial arc-back tests were made on rectifier section 3*B*, which is supplied by rectifier transformer number 3 rated at 6,550 kva with an equivalent impedance diagram similar to that shown in Figure 2. The schematic diagram of the main-circuit connections for the tests is essentially the same as that in Figure 5. An electronically controlled, short-circuiting switch was connected so as to short-circuit one ignitron tube. The currents flowing in the cathode and in the anode circuits of the 3*B* section were measured by a magnetic oscillograph with elements operated from shunts. During the artificial arc-back tests, the rectifier station was supplied from the Dow company's own power house, which was delivering 104,000 kw and 111,000 kva; a tie with the Houston Lighting Company was also in service. At the time of the tests, all rectifier sections in the station were carrying a load of 5,250 amperes per section at 648 volts direct current. The ignitor controls for each of the 12 rectifiers were carefully adjusted so that the sections carried 5,250 amperes each. All units were operating with some ignitor delay. All artificial arc-back tests were made from the same initial power-circuit conditions. However, the individual tests differ because the closing breaker applied the artificial arc-back at different points of the cycle.

Five artificial arc-back tests were made with this setup. Two oscillograms obtained during these tests are shown in Figures 11 and 12 which are representative of records with and without sympathetic arc-backs, respectively. The oscillograms show that each artificial arc-back was cleared by proper breaker operation. The d-c feedback was cleared by operation of the high-speed cathode breaker in a half cycle. The a-c circuit was cleared by the transformer primary-side breaker in nine to ten cycles from the inception of the artificial arc-back to the end of arcing between breaker contacts.

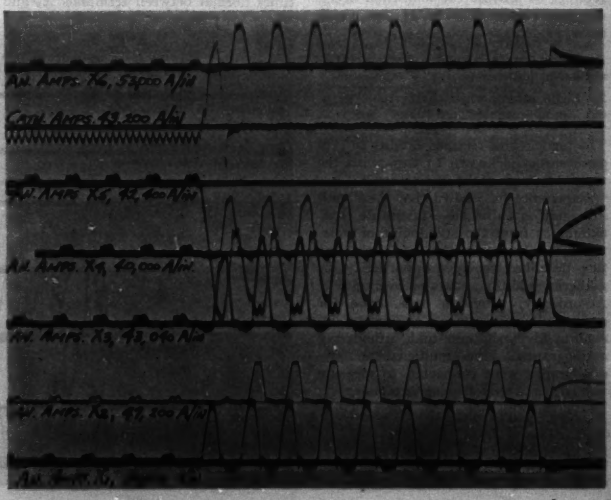
The characteristics of the d-c back feed, as given by these oscillograms, show a maximum rate of rise of current of 8,600,000 amperes per second, as defined by a tangent line from the beginning of reverse current to a high value of current before limitation by cathode-breaker operation. The maximum d-c back-feed current was 41,100 amperes, which was reached at a rate of 6,300,000 amperes per second.

Examination of the anode currents showed that artificial arc-backs of tests 1 and 4 produced sympathetic arc-backs but that those of tests 2, 3, and 5 did not. These conditions are shown in somewhat greater detail in Table I. On test 1, the ignitron of anode X_3 arced back in the first cycle but recovered and did not arc back again during the tests. Also on test 1 the ignitron of anode X_4 arced back at the end of the fifth cycle and did not recover until the end of the ninth cycle. On test 4, anode X_4 arced back at the end of the fourth cycle and did not recover again during the test. The crest values of anode currents in both forward and reverse directions for the different tests are also shown in Table I.

The oscillograms gave additional evidence that the highest initial arc-back current occurs when the arc-back is initiated at the end of the normal-conducting period, such as was obtained on tests 1 and 3. When an artificial arc-back occurs at this point and sympathetic arc-backs are not produced, the high initial crest of anode current on the first cycle is maintained at approximately constant value on succeeding cycles throughout the arc-back condition, that is, until cleared by

Figure 11. Oscillogram of artificial arc-back tests at Dow Magnesium Corporation, Velasco, Tex.

Simulation by short-circuiting switch. Artificial arc-back on phase 5. No sympathetic arc-backs encountered. Table II, test 3. See Figure 5



the a-c breaker. If the artificial arc-back occurs after the end of normal conduction and if a sympathetic arc-back does not occur, the anode current is initially considerably smaller but rises to approximately the same ultimate value as is obtained when the arc-back occurs at the end of normal conduction. If a sympathetic arc-back occurs, the anode that is subject to the initial arc-back subsequently has currents considerably below the initial arc-back value. Sympathetic arc-backs frequently increase the currents flowing in the anodes not subjected to arc-back.

Magnitude of Arc-Back Currents

A summary of the arc-back test data has been listed in Table II. This list is of particular interest in giving the ratios of the observed maximum arc-back current to the crest of the symmetrical three-phase short circuit on the particular star group subjected to arc-back. Of interest also is the ratio of the difference between the arc-back current and the back-feed current expressed as a ratio to the crest of the symmetrical three-phase short-circuit current on the particular star group subjected to arc-back. It will be observed that the arc-back current experienced in the field is appreciably lower than that in the laboratory. This is the result of the operating conditions which included an appreciable amount of voltage reduction by phase control.

Voltage Surges in Rectifier Circuits

One speculative problem of rectifier operation is the production of voltage surges. Theories for explaining rectifier surges[3] are based on the inability of the rectifier to provide the ionization necessary for current flow under two conditions, namely,

1. Heavy current as under short circuit or arc-back.

2. Light current when the current "snaps out" on approaching zero value.

The tendency of rectifier circuits to produce surges is known to vary with the type and design of the rectifier itself.

Experience has shown that the standard ignitron tubes have favorable characteristics from the standpoint of overvoltage. However, the arc-back test just described provided opportunity for gathering additional data on overvoltage. Accordingly, provision was made for surge voltage-measuring equipment including klydonographs and cathode-ray oscillographs. Five multielement klydonographs were connected to measure voltages between following terminals:

X_1, X_3, X_5, and C_1 to C_2
X_2, X_4, X_6, and N to C_1
Y_1, Y_3, Y_5, and C_2 to C_4
Y_2, Y_4, Y_6, and N to C_3
H_1, H_2, H_3 to ground

(See Figure 5)

Klydonographs were connected to the low-voltage side of the rectifier transformer during eight short circuits, 146 artificial arc-backs, 14 arc-backs in normal operation, and in addition a somewhat greater number of energizing operations. The klydonograph on the high-voltage side was connected for about 120 tests. Cathode-ray-oscillograph measurements were made for 21 tests between the high-voltage terminal and ground and for 47 tests on the low-voltage side either in parallel with klydonograph terminals or between anode terminals and ground.

Transient voltages below twice normal are of no importance and have been neglected in this investigation. On the high-voltage side one artificial arc-back test and the subsequent switching operation gave transient voltages of 4.8, 2.7, and 1.7 times normal on the three phases; two other tests gave voltages of 2.7 times normal on one phase and another test gave a voltage of 2.5 times normal on one phase. None of the cathode-ray oscillograms gave transient voltages on the high-voltage side to ground greater than 2.0 times normal. The cathode-ray oscillograph was connected for only a part of the total number of tests and by chance was not connected during the tests that gave the highest voltage. During one set of switching operations separate from an arc-back test, a transient voltage of 2.55 times normal was obtained on one phase.

On the low-voltage side the klydonograms showed voltages of 3.1 times normal between terminals X_4 and C_1 and between X_6 and C_1 on one test, and a voltage of 3.1 times normal between terminals X_1 and C_2 on another test. Cathode-ray oscillograms showed a voltage of 2.2 times normal between terminals X_1 and ground on one test, and a voltage of 2.1 times normal between terminals X_5 and C_2. The klydonograph is not well adapted for measuring the lower overvoltages on rectifier circuits for 600-volt output because it does not produce measurable voltages below about three kilovolts and may fail to record at all for voltages of about two kilovolts. The klydonograph, however, is capable of recording overvoltages as high as about 15 kv, and, therefore, should have recorded high surges had they been encountered. The cathode-ray oscillograms showed many records in the vicinity of twice normal but no records inconsistent with the klydonograms.

One of the possible methods of producing voltage surges in a transformer obtains when circuit breakers on the a-c and d-c sides are switched simultaneously. Fifteen artificial arc-back tests were made with the a-c breaker pretripped by a sequence drum so as to approximate simultaneous operation of a-c and d-c breakers. In none of these tests was any appreciable overvoltage recorded on either klydonograms or cathode-ray oscillograms. Possibly one reason for the absence of overvoltages arises from the fact that an artificial arc-back provides a path for the discharge of reactive energy in the rectifier transformer, and sympathetic arc-backs provide additional paths. Current flows in these paths after d-c and a-c breakers are opened as shown by several of the oscillograms, such as Figures 8 or 10. In view of the absence of overvolt-

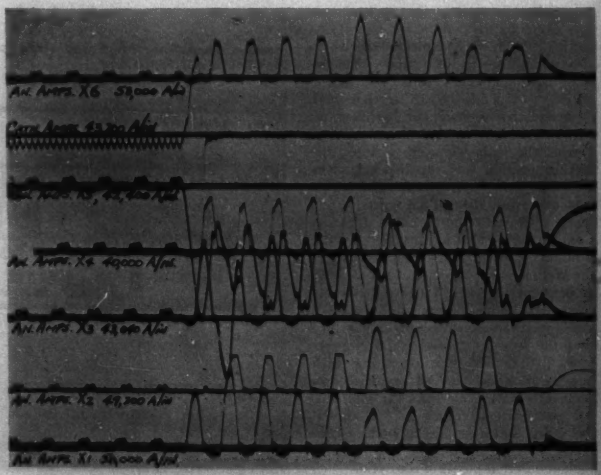

Art. Anode X6 53,000 A/in
Cath. Anode 43,200 A/in
Art. Anode X3 42,000 A/in
Art. Anode X5 43,000 A/in
Art. Anode X2 42,200 A/in
Art. Anode X1 50,000 A/in

Figure 12. Oscillogram of artificial arc-back tests at Dow Magnesium Corporation, Velasco, Tex.

Simulation by short-circuiting switch. Artificial arc-back on phase X_5. Sympathetic arc-backs encountered on phases X_6 and X_4. Table II, test 1. See Figure 5

ages during these tests and the improbability of simultaneous switching operations occurring in practice, it is apparent that voltage surges from this cause are unlikely to be of practical importance with ignitrons.

Another series of laboratory tests was made to determine whether abnormal operating conditions would cause the standard ignitron tank to show a tendency for the production of surges. Six short-circuit tests were made with a normal 3,000-kw 600-volt rectifier starting with cooling water at the normal temperature of 52 degrees centigrade. Three of these tests started from a load of 1,000 amperes and three from no load. Of these, four were cleared on the d-c side by a semihigh-speed breaker and two by a high-speed breaker. No arc-backs were encountered during these tests. Eleven short-circuit tests then were made with the rectifier cooling water starting at the unusually low temperature of 19 degrees centigrade. Of these tests, four started from an initial load of 1,000 amperes and the remainder from no load. Because of the unusually low cooling-water temperature the short circuits in many cases were accompanied by arc-backs, particularly when starting from no load. On none of these tests were any surges recorded by klydonographs connected to the low-voltage side of the rectifier transformer in the manner previously described.

Surge-voltage measurements were also made in the field and klydonographs were installed in two electrochemical plants to measure the transient voltages on the low-voltage side of one rectifier transformer in a manner similar to that previously described in connection with the laboratory tests. In a plant equipped with anode-breaker switching, operated by the Aluminum Company of America at Alcoa, Tenn., no surges were recorded by the klydonographs during a month's operation in which two arc-backs, one miscellaneous automatic operation, and nine energizing and de-energizing operations took place. In a plant equipped with cathode-breaker clearing operated by the Dow Chemical Company at Velasco, Tex., no surges were recorded by klydonographs during a period in which 15 arc-backs and a corresponding number of energizing and de-energizing operations took place.

This investigation of voltage surges on rectifier circuits has included voltage measurements during a large number of arc-backs accompanied by energizing and de-energizing operations. In none of these tests were voltages greater than 3.3 times normal obtained on the low-voltage side. The highest transient voltages measured were 3.3 times normal measured with a cathode-ray oscillograph; the three next highest voltages of 3.1 times normal were measured with klydonographs. Only five tests gave transient voltages in excess of three times normal and none of the remaining measurements exceeded either 2.2 times normal or exceeded three kilovolts (the minimum definitely measurable voltage of the klydonograph). Out of over 100 artificial arc-back tests, transient voltages measured on the high-voltage side of the rectifier transformer showed only one case with a voltage as high as 4.8 times normal and only five cases greater than 2.5 times normal.

The switching surges on the high-voltage side of the transformer are believed to have resulted from the disconnection of the circuit following the arc-back. This is shown from the character of the oscillograms. Additional evidence along this line is also given by one switching operation separate from an arc-back test which caused a surge of 2.55 times normal. While a switching surge of 4.8 times normal is relatively high, it is within the usual limits of four to six times normal to be expected occasionally on switching surges.[8,9] All these transient voltages are well below the basic insulation levels of normal transformer design.

With phenomena that are believed to occur but seldom or never, it is, of course, difficult to reach conclusions from tests which give negative results. Nevertheless, results of this investigation of rectifier surges are reassuring.

Conclusions

This paper has presented the results of an extensive series of artificial arc-back tests that have provided additions of value to the published information on the magnitude and character of arc-back currents.

The artificial arc-back tests have shown that the arc drop in the ignitrons used in the larger electrochemical installations constitutes an important factor in limiting arc-back currents.

These artificial arc-back tests provided extensive measurements of transient voltages experienced on rectifier circuits without giving evidence of surge voltages other than those normally associated with the switching operations incident to the disconnection of the a-c supply to the transformer associated with a rectifier under arc-back conditions. The results of this investigation for voltage surges while negative in character are, nevertheless, reassuring from the standpoint of practical operating experience.

The nature and cause of sympathetic arc-backs have been analyzed and shown to be dependent upon the previous magnitudes of forward-flow current. Data are presented on this current limit for a standard ignitron tube.

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Power Geometry of General Transmission Systems

WM. ALTAR
ASSOCIATE AIEE

IN its present known form[1-6] the power-circle diagram of a transmission system applies to operating conditions where constant voltages are maintained at both the sender and the receiver. While this is by far the most frequent type of operation, instances are numerous where the designer or analyst is confronted with conditions requiring only one of these two voltages to be constant. This is true particularly when the concept of a transmission system is taken in a broader sense as applied to a generator, motor, transmission line, or generally speaking, to any part of a composite transmission system. To mention but one example, the induction motor may be considered a transmission system which supplies power in varying amounts to an equivalent electric load of unity power factor, and its circle diagram accordingly is of a different character. From a viewpoint which looks at all equipment having input and output terminals as general transmission systems, it seemed desirable to formulate on a broader basis the relations between sender and receiver power as exemplified by the constant-voltage circles of the conventional sender and receiver charts. Moreover, a more general relation will permit the translation from one chart to the other, not only of actual power loci of operation, but also of efficiency contours, contours of loss, power factor, receiver wattage and amperage, and other concepts of interest. As it happens, all these cases fall into the wider class where

(*a*). The voltage is maintained constant at one terminal point of the system.

(*b*). The operating locus or contour is a circle for this terminal point.

For the sake of brevity, the sender end through most of the following will be considered as the terminal point with constant voltage, a restriction which is merely one of nomenclature and sign convention.

While the extension of the theory to this wider class of loci was being studied a simple geometrical relationship was established between coexisting diagrams in the two charts. Its existence is obscured in the conventional presentation of power circles, because it is customary to plot sender and receiver charts either separately, or else in one and the same reference frame. For the formulation of the new relation, on the other hand, it is obligatory that the charts be plotted in two different co-ordinate systems which are tilted and displaced against one another to an extent computable from the circuit properties of the system. We shall use the term "power-chart transformation" for the geometrical procedure which carries points of the sender chart collectively into their coexisting points in the properly placed receiver chart. The transformation is such as to transform circles into ellipses. Fortunately, these elliptical receiver loci degenerate in all cases of practical interest into a circle, a parabola, or a terminated straight line, all of which can be constructed easily because of the adopted choice of receiver chart axes. No equally simple and direct procedure exists when the two charts are plotted in the conventional manner.

By resorting to a third dimension one can interpret the power-chart transformation as a projective relation, similar in character to the so-called stereographic projection which in a different way already has proved useful in other branches of circuit theory.[7] This makes the relationship between the charts exceedingly simple to visualize and at times points an easier way for graphical procedure in the chart plane.

The proposed choice of receiver axes proves its advantage most strikingly when it enables us to trace an operating locus or contour on one, say the receiver chart, with the help of points from the other chart. This may be illustrated by the so-called envelope which is the boundary on the receiver chart of the accessible load range.[8] As explained in the section on limiting parabola, the parabola has the open-circuit point as its focus and its directrix is the line which bisects the distance between open- and short-circuit points. This statement involves two points of the sender chart and a curve on the receiver chart, and its meaning is clearly contingent upon the particular choice of reference frames.

It is gratifying that the graphical procedure thus resolves itself into two distinct steps, one exclusively concerned with the circuit properties of the system, the other exclusively with specified operating conditions or contours. The circuit properties determine the manner in which the sender and receiver frame are laid out, but do not enter explicitly into that part of the procedure where the sender or the receiver locus is found graphically from the other. In fact, the second step follows a standard pattern no matter whether one deals with the simplest conceivable case of an impedance line in series with the load, or with the most elaborate four-terminal network.

Before discussing the general procedure as applied to an arbitrary sender circle, contours of practical interest likely to occur in actual problems are discussed, beginning with the familiar power-circle diagram and its modification. All numerical illustrations are derived from a balanced three-phase transmission system, one phase of which is represented in Figure 1 by its equivalent π-circuit. In assuming numerical values, the real part of Y_1 has been exaggerated in order to emphasize the asymmetry of the network. It is not actually a necessary part of the procedure to reduce a given system to its π-circuit because the characteristic chart points can be computed directly, or found by measurement.

Points S and O, recurring in Figures 3 to 9, are the end points of the two vectors of complex sender power $(P+jQ)$ when rated voltage $E_s = 240$ kv line-to-line is applied to the sender terminals, and the receiver end is short-circuited or, respectively, open; thus

$$\left.\begin{aligned}(P+jQ)_{ss} &= \frac{240^2}{768-576j}+\frac{240^2}{23.6+160j}\\ &= (100-316.3j)\text{ mva}\\ (P+jQ)_{so} &= \frac{240^2}{768-576j}+\frac{240^2}{23.6-1{,}440j}\\ &= (54.5+76.0j)\text{ mva}\end{aligned}\right\}\quad(1)$$

Reversing the direction of transmission one obtains the receiver-end short-circuit power

$$(P+jQ)_{rs} = \frac{240^2}{-1{,}600j}+\frac{240^2}{23.6+160j}$$
$$= (52.0-316.3j)\text{ mva}$$

Point N (Figure 4) is obtained by plotting in the sender chart the difference $(P+jQ)_{ss}-(P+jQ)_{so}$ and, for symmetric sys-

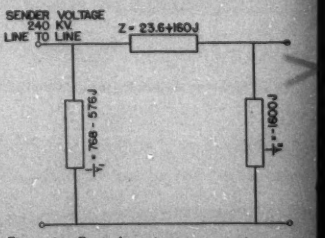

Figure 1. Equivalent circuit representing one phase of balanced transmission system

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WM. ALTAR is in the research laboratories, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

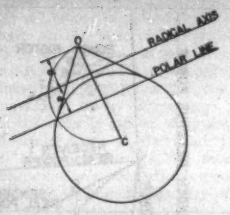

Figure 2. Radical and polar axes of a circle and a point O

tems, coincides of course with the origin of the sender chart.

With the help of these points the receiver chart is laid out with its origin at O, and the orientation of its axes is obtained by rotating the sender axes through that angle 2δ, and in that sense, by which the vector $\boldsymbol{SN}$ would be tilted into the direction $\boldsymbol{SO}$ (Figure 4). The axes so obtained are subdivided in divisions equal to the units of the sender scale.

With the two frames thus laid out, it is quite generally true that all lines connecting a pair of coexisting points on the two charts are parallel to line SO; a rule which greatly simplifies the identification of such pairs.

The only geometrical concept likely to strike the reader as unfamiliar is the so-called radical axis[3] of a circle and a point O. The radical axis is the straight line r (Figure 2) which passes halfway between the point O and the polar axis of O and the circle. Figure 2 indicates how r may be determined graphically. Frequent reference will be made to the straight line which perpendicularly bisects the distance SO, and for which we shall use the letter b.

It sometimes is preferable to represent the system by its three characteristic points O, S, and M instead of O, S, and N. To find M (Figure 4) one draws a line through S, bisecting the angle between vectors $\boldsymbol{SN}$ and $\boldsymbol{SO}$, thus obtaining the direction of vector $\boldsymbol{SM}$. Its length is the geometrical mean of SN and SO. Or algebraically

$$\boldsymbol{SM} = \sqrt{SO\,SN}$$
$$= \sqrt{(45.5-392.3j)(52-316.3j)} \qquad (2)$$
$$= 356.3\epsilon^{-j82.9^\circ}$$

The Conventional Diagram and Its Modification

For purposes of comparison, Figure 3 shows the sender and receiver circle constructed in the customary manner[4] for the system of Figure 1, operated at constant sender voltage $E_s = 240$ kv line-to-line, and constant receiver voltage $E_r = 200$ kv. In the conventional procedure, provision is made for identifying pairs of coexisting points by locating the pair for which Θ_s is zero, that is, where sender and receiver voltage are in phase. Other pairs then can be identified by laying off equal angles Θ_s on the two circles.[2]

If we now move the receiver circle, together with its reference frame, to their new positions as previously described, we have the following changes (Figure 4). Centers S and s fall on a straight line with point O; the radical axis r of the sender circle and O is an axis of symmetry for the two circles; coexisting point pairs lie on straight lines parallel to SO, so that the quantity Θ_s; and the construction of a reference pair is no longer needed. When needed, the reference pair with $\Theta_s = O$ can be found easily since the sender point is the intersection of the sender circle and line SM. More specifically, the vector $\boldsymbol{SM}$ may serve as a reference vector representing E_s. For an arbitrary load condition, represented by point P in the sender chart, the vector $\boldsymbol{E_r}$ is then represented by vector $\boldsymbol{SP}$ both in magnitude and phase.* Consequently, for a receiver voltage $E_r = 200$ kv, both the sender and receiver circle have a radius

$$\overline{SM}\,\frac{200}{240} = \frac{356.3}{1.20} = 296.9 \text{ mva}$$

The center of the sender circle is S, while that of the receiver circle may be found graphically by drawing the radical axis r of the sender circle and O, which one knows to be an axis of symmetry for points S and s. Comparing Figures 3 and 4, it will be noted that vector $\boldsymbol{SM}$ is identical with E_s^2/Z of Figure 3.

The Limiting Parabola

In the manner of the preceding section, a number of receiver circles of different radii may be found, each representing a different value of E_r. The envelope of these circles, which is of occasional interest in connection with system stability, is a parabola. When plotted in the properly placed receiver frame (Figure 5), the parabola has the point O as its focus, and the line b as its directrix, and thus may be traced easily as the locus of all points having equal distances from point O and line b. Line b marks the coexisting locus on the sender chart, and transmission systems operate exclusively above this line. Also shown on Figure 5 is the receiver circle of Figure 4, tangent to the parabola at two points.

Contours of Load Power Factor

Unlike the preceding cases, this requires the determination of the sender locus from the given receiver locus, which is a straight line g through the receiver origin. Consequently,** the sender locus is a circle through O and S and tangent to g (Figure 6). It is more accurate to describe the receiver locus g, not as a straight line, but

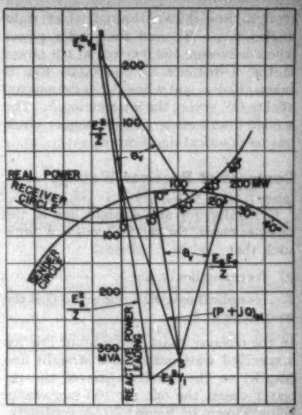

Figure 3. Conventional circle diagram for system of Figure 1, when receiver voltage is maintained at 200 kv line to line

as an ellipse collapsed into a straight-line section, the terminating points being points of the parabola of Figure 5 or, alternatively, the extreme points on g to be reached by projecting points of the circle in the direction SO. From Figure 6 it will be seen that any two points on the sender chart which are situated symmetrically relative to line b give rise to the same receiver power, and so the two halves of the sender plane each equally are transformed by the power-chart transformation into the receiver-chart region which lies inside the parabola.

In Figure 6 is shown the sender locus for a load power factor 0.90 lagging. Its center C is the intersection of b and a

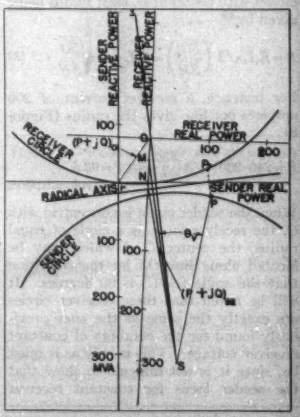

Figure 4. Modified form of circles for constant sender and receiver voltage

* See Appendix I. The proof of the statement is contained in equation 8.

** See Appendix II, case 3.

straight line drawn through O at right angles to g. To find the sender power when delivering 100,000 kva at 0.9 power factor, a distance OP_r=100,000 kva is taken along g, and a line PP_r is drawn parallel to OS, giving the intersection P. The second intersection with the sender circle has no practical significance.

Contours of Receiver Wattage

Generally, for any straight line in the receiver chart, the sender locus is a circle such that:

1. Its center lies on line b.
2. Its radical axis with respect to O is the receiver locus.*

In the receiver chart, the contour line for a specified watt output is a straight line parallel to the reactive axis of the receiver chart, the one for 100 megawatts being shown in Figure 7. Accordingly, all sender contours are concentric circles, their center C being the intersection of line b and the real axis of the receiver chart (not shown in Figure 7). To find the radius, draw a semicircle over OC, and a line p parallel to the receiver locus r at twice the distance (200 megawatts) from O. Line p is the polar axis of O and the desired circle; its intersection with the semicircle is A. The radius of the wanted sender circle is CA. Shown in Figure 7 is the pair of points which was used previously in different connection in Figure 4. The receiver locus is again an ellipse collapsed into a terminated straight line and extending across the inner region of the limiting parabola.

Contours of Receiver Amperage

In the sender chart the contours of constant receiver current I_r are concentric circles with center at O, their radius being given by**

$$R = E_s I_r \sqrt{3} \left(\frac{\overline{SO}}{\overline{SM}}\right) = E_s I_r \sqrt{3} \sqrt{\frac{\overline{SO}}{\overline{SN}}} \qquad (3)$$

For instance, a receiver current of 200 amperes per line gives the radius (Figure 8)

$$R = 240 \cdot 200 \cdot \sqrt{3} \cdot \frac{356.3}{320.6} 10^{-3} = 92.5$$

megavolt-amperes

When the sender circle is concentric with O, the receiver locus is a circle of equal radius, the center C of which may be located along line OS by the condition that the angle (SDC) is 90 degrees. It will be noted that these receiver circles are exactly the same as the ones previously found for the contours of constant receiver voltage. This is only as it must be, since it is not difficult to show that the sender locus for constant receiver voltage V is the mirror image relative to line b, of the sender locus for constant receiver current I_r when the latter is numerically equal to the short-circuit current I_{sc} obtained when voltage V is placed at terminals 2 and terminals 1 are short circuited.

The contours of receiver voltage and of receiver amperage are the only ones giving circles in both charts.

The General Relation Between the Two Charts

These illustrations will suffice to give an idea of the possible use of the procedure for graphical analysis. It will not be necessary to produce individual proofs of the rules stated in foregoing sections, since they are all special cases, or corollaries, of the general theorem which gives the receiver locus (an ellipse in general) for a sender circle of arbitrary position and radius (Figure 9).

In order to determine the receiver ellipse, the radical axis r of the sender circle and point O is drawn, and point $\bar{C}$ is placed symmetrically to C with respect to line r. Next the center C' of the ellipse is found by means of the requirement that the two point triples (O, S, C) and (C, $\bar{C}$, C') form similar triangles. Inspection shows that points O, S, and C are respectively homologous to points C, $\bar{C}$, and C', and follow each other in opposite sense (that is, O, S, C clockwise; C, $\bar{C}$, and C' counterclockwise in Figure 9). Other points P_r on the ellipse can be found by a variety of methods, for instance, by choosing an arbitrary point G on r and using the similarity of triangles (G, C, C') and (H, P, P_r); homologous lines being parallel to each other. However, the usefulness of Figure 9 lies principally in its general validity which permits the derivation of the specific rules given in the preceding sections. This will be shown in the appendix.

The general character of the power-chart transformation as applied to a sender

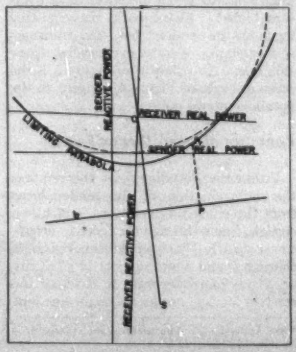

Figure 5. Limiting parabola

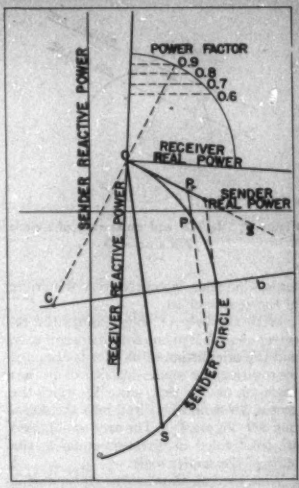

Figure 6. Sender contour of constant load power factor 0.9, lagging

circle may be visualized by imagining that Figure 9 shows in perspective two boards in space, meeting at an angle along line r. A circular hole in the lower board, representing the sender circle, when illuminated by a distant source in the direction SO will throw an elliptical shadow of the kind shown in the figure.

Another way of visualizing the relationship is preferable, because it represents at once the entire charts instead of just one circle at a time. In Figure 10 is shown the chart plane with its two reference systems in perspective. A sphere of arbitrary radius is placed in contact with the sender chart, point O being the point of tangency and the south pole of the sphere. Points of the sender chart then can be projected on the sphere in the direction toward the north pole A, thus representing the sender chart on the sphere by what is known as stereographic projection. In particular, the image of the short-circuit point is thus obtained on the sphere, and through it and through point O a straight line is drawn up to point B, that is, to its intersection with another horizontal plane tangent to the sphere at its north pole A.

Now, in order to determine the receiver point from the given sender point, it is only necessary to transfer the latter to the sphere by stereographic projection from A, and to project the obtained images back from the sphere into the receiver chart using point B as the center of projection, as shown in Figure 10. Proof that this procedure is mathematically equivalent to the two-dimensional procedure (as embodied in Figure 9) will be found in the last part of the appendix. Lacking a better name, it will be referred to as the

* See Appendix II, case 2.

** See Appendix I. The proof of the statement is contained in equations 8.

"modified stereographic projection." A simple mechanical or optical device could be built on the basis of the projective relation, for example, one providing two arms hinged to A and B respectively, and so linked with each other that one arm automatically traces the receiver locus while the other is guided along any desired sender locus in the chart plane. More important, perhaps, the modified stereographic projection affords a concise formulation of the peculiarities of the

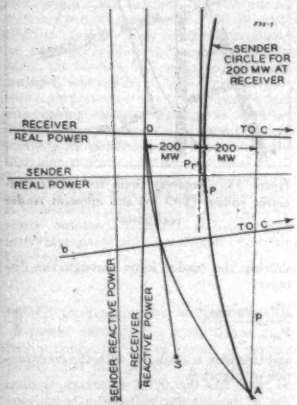

Figure 7. Sender contour of constant receiver wattage (200 megawatts)

power-chart transformation. For instance, we see why circular sender curves must give rise to ellipses in the receiver chart. This is so because sender circles are always stereographically represented as circles on the sphere which are then subjected to reprojection from the center B. Again, the general rule that the direction sender–receiver point is always parallel to SO follows geometrically from the fact that corresponding point pairs lie in a plane with A and B, as do points S and O. Line AB is parallel to SO and to PP_r, thus proving our rule.

The limiting parabola permits a neat visualization in terms of the modified stereographic projection, being the border line of the shadow which the sphere will cast on the receiver chart when illuminated by a point source at B. The shadow clearly must be a conic section, and more specifically a parabola since the light source B is at the same height as the north pole A. It becomes a simple problem in geometry to verify its exact location and the fact that the borderline of the illuminated region on the sphere is the stereographic projection of line b.

It also will be seen that any straight line in the sender chart gives a circle through A by stereographic projection on the sphere, and in the receiver chart a parabola by reprojection from B. Occasionally, it may be helpful to know that the radical axis of an arbitrary sender circle and O lies in the same plane as the stereographic image of the circle on the sphere.

Operation With Constant Receiver, Variable Sender Voltage

The power-chart transformation also can be established if the receiver terminals instead of the sender terminals are operated at constant voltage. To reformulate our statements for this case, it is merely necessary to interchange the words "sender" and "receiver" whenever they occur and to reverse the signs of all power vectors, for example, by rotating the diagram of sender and receiver chart as a whole through 180 degrees. The letters S and O now mean short-circuit and open-

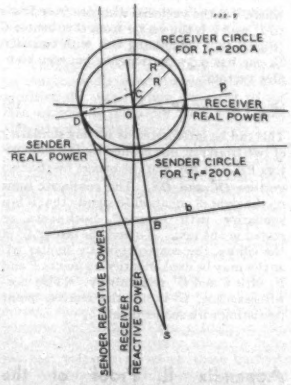

Figure 8. Sender and receiver contours of receiver current (200 amperes per line)

circuit power measured "looking backward,"[8] that is, with rated voltage at receiver terminals and the sender end short circuited or, respectively, open. As an illustration, Figure 11 shows the diagram for the system of Figure 1, operating with constant receiver voltage of 240 kv line-to-line and constant real power at the sender. (If the circuit of Figure 1 included the generator synchronous impedance, assumed constant for the sake of arguments, this would give the receiver contours of prime-mover $HP = 2.0 \times 10^5$.) Points S and O are determined by plotting on the receiver chart the two vectors $-(P+jQ)_s$ and $-(P+jQ)_o$, respectively, the latter being

$$-\left(\frac{240^2}{-1{,}600j}+\frac{240^2}{791.6-416j}\right)=-57.0-66.0j$$

Point N has the same position on the receiver chart which it previously (Figure 4) had in the sender chart. The angles $2\delta'$ and 2δ are not equal. Otherwise, the construction is very much like the one outlined in Figure 7 except that the words "sender" and "receiver" are reversed; a circular receiver locus now corresponds to the sender locus g, the latter being the radical axis of the receiver locus relative to the point O.

Appendix I. Power-Chart Transformation Applied to a General Sender Circle

The construction embodied in Figure 9 will be established by first deriving a generally valid complex vector equation for sender and receiver power. The fundamental line equations

$$E_r = E_s(ZY_1+1) - IZ \qquad (4a)$$

$$I = -E_s(ZY_1Y_2+Y_1+Y_2)+I(ZY_2+1) \qquad (4b)$$

can be reduced to a form not involving the circuit elements Z, Y_1, Y_2. Thus, one avoids the need for representing given transmission systems by equivalent circuits. Setting E_r in equation 4a and I_r in equation 4b alternatively zero, one finds the short-

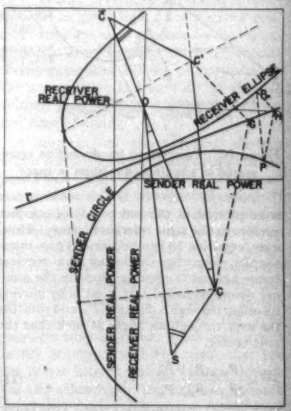

Figure 9. Receiver locus for an arbitrary sender circle

circuit current and, respectively, the open-circuit current of the system

$$I_{s1} = E_s\frac{ZY_1+1}{Z} \text{ and } I_{o1} = E_s\left(Y_1+\frac{Y_2}{ZY_2+1}\right) \qquad (5)$$

To eliminate the circuit elements we introduce the quantity I_m, meaning the current which flows in the short-circuiting strap at short circuit. Thus

$$I_{sm} = E_s/Z = \sqrt{I_{s2}(I_{s1}-I_{o1})} = \sqrt{I_{s1}(I_{s2}-I_{o2})} \qquad (6)$$

n terms of which

$$Z=E_s/I_m,\ E_sY_1=I_{s1}-I_m,\ E_sY_2=I_m-I_m \quad (7)$$

Introducing equation 7 into equation 4 we have

$$E_r=E_s\frac{I_{s1}-I}{I_m} \text{ and } I_r=I_m\frac{I-I_{s1}}{I_{s1}-I_{s1}} \quad (8)$$

from which the receiver power vector is obtained by complex multiplication

$$(P+jQ)_r=\bar{E}_rI_r=\bar{E}_s\frac{(I_{s1}-\bar{I})(I-I_{s1})}{(I_{s1}-I_{s1})}\frac{I_m}{\bar{I}_m} \quad (9)$$

Since the sender voltage is constant, each current vector on the right hand of equation 9 is turned into a complex power vector by multiplication with $\bar{E}_s$. Using the short notation P for $(P+jQ)=\bar{E}_sI$, and similarly $P_r=(P+jQ)_r$, $P_{s1}=\bar{E}_sI_{s1}$, $P_m=E_sI_m$, and so forth, equation 9 is changed to

$$P_r=\frac{(\bar{P}_{s1}-\bar{P})(P-P_{s1})}{(\bar{P}_{s1}-\bar{P}_{s1})}\frac{P_m}{\bar{P}_m} \quad (10)$$

Equation 10 could be interpreted as a complex equation between points P, P_r if both

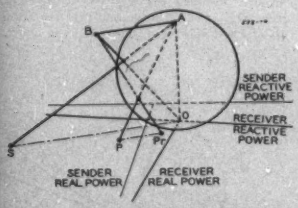

Figure 10. Power-chart transformation represented as a projective relation in space

were plotted as the end points of complex vectors in the same reference frame. However, equation 10 can be reduced to a much simpler form by displacing the receiver frame against the sender frame in the manner described in the text, that is by moving its origin through a distance P_{s1} and rotating the axes through an angle 2δ such that the unit vector

$$e^{j2\delta}=\frac{(P_{s1}-P_{s1})}{(\bar{P}_{s1}-\bar{P}_{s1})}\frac{\bar{P}_m}{P_m} \quad (11)$$

With reference to this new receiver frame, points which in the sender chart represent a power vector P are then represented by P'

$$P'=(P-P_{s1})e^{-j2\delta} \quad (12)$$

$$P_{s1}'=(P_{s1}-P_{s1})e^{-j2\delta} \text{ and } P_{s1}'=\text{zero} \quad (12a)$$

while points representing receiver power are, of course, still given by P_r. Introducing equations 11, 12, and 12a, into equation 10 changes this equation to

$$P_r=\frac{(\bar{P}_{s1}-\bar{P})(P-P_{s1})}{(\bar{P}_{s1}-\bar{P}_{s1})}e^{-j2\delta}=\left(P-\frac{\bar{P}\bar{P}}{\bar{P}_{s1}}\right)'$$

or

$$P'-P_r=\frac{\bar{P}'^2}{\bar{P}_{s1}'} \quad (13)$$

Equation 13 has formally the simplicity which equation 10 would have when applied to an impedance line. Omitting primes for this case, one finds equation 13 reduces to

$$P-P_r=\bar{I}^2(R-jX)$$

As equation 13 is quite general, one can borrow the circle diagrams of the impedance line for use in the general case.

Proof of the geometrical relation embodied in Figure 9 rests on equation 13. We shall use the symbol $\overline{OS}$ to indicate the vector pointing from S to O and so forth, so that $\overline{PP}_r=(P'-P_r)$, $\overline{OS}=P_{s1}'$ and so forth. Now it is a known property of the radical axis that its distance x from an arbitrary point P on the circle is proportional to the square of distance $\overline{OP}$, thus

$$\overline{OP}^2=2x\overline{OC}$$

or in complex notation, using vectors in the receiver chart

$$P'\bar{P}=2x\bar{c} \quad (14)$$

where x is the vectorial distance from line r to P, and c is the vector from O to center C (Figure 9). Combining this with equation 13 one has a proportionality between complex vectors

$$(P'-P_r):2=\bar{c}:P_{s1}' \quad (15)$$

This can be interpreted as stating similarity of two triangles, one formed by the two vectors $\overline{PP}_r$ and $\overline{PP}$, and the others by the two vectors $\overline{OC}$ and $\overline{OS}$. The conjugate signs on the right of equation 15 signify that it is a similarity with inverted clock-sense as stated in the text. To find the center C' of the ellipse, the construction by similar triangles may be used, identifying points P and P_r with C and C', respectively. (This notwithstanding, C' is not the receiver point coexisting with sender point C.)

Appendix II. Proof of the Corollaries Used in This Paper

Case 1. Contours of Constant Receiver Voltage. Since the sender circles have their center at S, points S and C in Figure 9, and consequently points P_r and P, coincide. This means that sender and receiver points are symmetrically situated with respect to r.

Case 2. Contours of Constant Receiver Wattage. The sender circle has its center on b, making the triangles (OSC) and (PP_rP) of Figure 9 isosceles, so that point P_r lies on a line which perpendicularly bisects $\overline{PP}$, that is, on the radical axis r. Conversely, whenever the receiver locus is a straight line, it is the radical axis of the sender circle and point O.

Case 3. Contours of Load Power Factor. The straight line of case 2 passes through O, reducing the radical axis to the tangent at O. The sender circle passes through O and, having its center on b, through S also.

Case 4. Contours of Receiver Amperage. The sender circle has its center at O so that the quantity P' of equation 13 is of constant amount. The receiver locus is obtained by

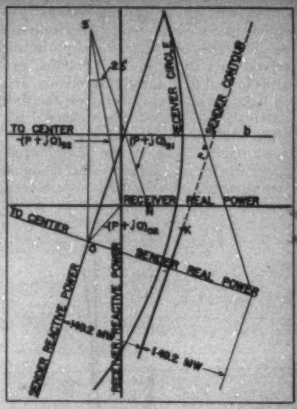

Figure 11. Receiver circle for constant receiver voltage (240 kv) and constant sender real power

shifting the sender locus through the distance

$$\frac{\overline{P'^2}}{P_{s1}}=\frac{(\text{radius})^2}{\overline{OS}}$$

and this is in accordance with the construction of Figure 8.

Appendix III. Proof of the Modified Stereographic Projection

As shown in the text, the modified stereographic projection gives correctly the direction from sender to receiver point as parallel to SO. Since any arbitrary sender point can be defined as the intersection of one such line with a sender circle of constant load power factor, it will be sufficient to show that these sender circles are correctly given by the modified stereographic projection.* Now referring to Figure 10, if the receiver locus is a straight line g through O, the corresponding circle on the sphere lies on a plane through line g and point B, a plane which also contains the stereographic image of point S. It follows that the sender circle, obtained by projection from A, must pass through O and S, and be tangent to g, which was to be demonstrated.

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The Next Step in Interrupting Capacity—5,000,000 Kva

A. W. HILL
MEMBER AIEE

W. M. LEEDS
MEMBER AIEE

Synopsis: Serious consideration is being given to large power-system interconnections which could develop short circuits at certain locations in excess of 3,500,000 kva. High-voltage oil-circuit-breaker capabilities for such heavy duty are reviewed in this paper, the fundamental design requirements outlined, and results of high-power laboratory tests presented which demonstrate that interrupting capacity ratings as high as 5,000,000 kva are feasible. Laboratory test methods for demonstrating these extremely high arc rupturing ratings are evaluated. The importance of verifying high-speed reclosing performance with high-power tests is emphasized, and on the basis of data already obtained, standard reclosing time intervals considerably less than 20 cycles are foreseen.

THE interconnection of large electric-power systems has resulted in such heavy concentration of power at certain points that the possibility of short circuits in excess of 3,500,000 kva must be considered. Whether advantages of solidly tied together "super-power" systems are to be fully realized may depend in considerable measure on the adequacy of the protective equipment. This paper reviews the present status of high-voltage oil circuit-breaker design and development, with particular emphasis on the requirements for interrupting capacity ratings as high as 5,000,000 kva in the 138-kv, 161-kv, and 230-kv voltage classes.

Performance Requirements for 5,000,000-Kva Oil Circuit Breakers

In the rating of high-voltage oil circuit breakers for 5,000,000 kva, the item which demands the most critical attention is the interrupting capacity. Insulation tests, continuous and short-time current carrying ratings, and mechanical operating speeds need not involve any serious departure from conventional practices. However, the arc-rupturing ability cannot be predicted accurately, and assurance of adequacy requires actual short-circuit testing along the following lines:

1. Voltage interrupting ability should be demonstrated to at least 87 per cent of line-to-line voltage across a single pole at whatever current values are available. For the 138-, 161-, and 230-kv ratings under consideration, these minimum test voltages would be 115-, 140-, and 200-kv respectively. Interrupters which show very little increase in arcing time as the voltage is raised are particularly favorable to methods of extrapolation where full rated short-circuit power is not available for testing.

2. Voltage-recovery rate may be an important consideration, depending on how sensitive the interrupting device is to the rate of rise of recovery voltage.[1] Most high-power laboratory circuits have a recovery rate in excess of 1,000 volts per microsecond for the higher current range. However, it should be pointed out that verification tests on a power system will have a very much lower rate because of the added capacitance of transmission lines and the overvoltage damping effect of parallel loads connected to the bus at the time of test.

3. Current-interrupting ability should be shown by short-circuit tests up to the full current values of 21,000, 18,000, and 12,500 amperes for 5,000,000-kva ratings at 138, 161, and 230 kv respectively, using the highest test voltages at which these currents may be obtained. Still better are tests in which the rated short-circuit currents are interrupted by a subdivision, such as a half pole of the breaker, across which normal voltage for that particular section can be applied, as discussed under test methods.

4. High-speed reclosing of oil circuit breakers is generally recognized as involving additional severity in short-circuit interrupting duty when there must be a second interruption after an interval of only a fraction of a second. For two operations in such close succession, it has been customary to use an interrupting rating factor of 75 per cent for ratings between 10,000 and 20,000 amperes, and 65 per cent for ratings between 20,000 and 40,000 amperes. If these factors are applied to 5,000,000-kva breakers the interrupting capacity at 161 kv and 230 kv would be reduced to 3,750,000 kva for rapid reclosing duty, and at 138 kv to 3,250,000 kva. Since intervals of 20 or 30 cycles do not, in general, allow time for the gas produced by one operation to be completely replaced by oil in the interrupting units before the next operation, it is essential that full voltage and current per unit be used in demonstrating the adequacy of the breaker for high-speed reclosing duty.

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A. W. HILL and W. M. LEEDS are both in the switchgear engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

High-Voltage Oil-Circuit-Breaker Design

There are a number of factors which affect the interrupting capacity of a high-voltage oil circuit breaker. It is taken for granted that modern oil circuit breakers require some type of arc extinguishing device in order to provide sufficiently effective arc-rupturing action to meet present day high-speed interrupting time ratings. High effectiveness is indicated by low tank pressures and small quantities of gas generated. For a given contact velocity and current to be interrupted, it is evident that the total amount of gas generated will be proportional to the arc energy, and in turn to the arc voltage per inch of contact separation and time of arcing.

A number of arc-rupturing devices which use self-generated arc extinguishing power have the characteristic of reduced arcing time as the current increases. If the short-circuit current is raised higher and higher, eventually one of two things will result to set a limit on the interrupting capacity. In the first place, the interrupting effectiveness may be impaired by insufficient oil supply in the arc chamber, or choking of the vent passages may leave too much ionized gas in the arc space with the result that the arc is not interrupted and failure occurs. On the other hand, the internal pressure generated during the arcing period may reach values sufficient to rupture the arc chamber so that the ability to function on subsequent operations would be lost even if arc interruption should occur on the operation during which damage occurred. If prompt back-up protection is not provided, continued arcing may result in splitting open the tank itself.

It has been found experimentally that, not only is the internal pressure proportional to the total arc energy, but superimposed high-pressure impulses are present which are a function of the rate of arc energy liberation, in other words to the instantaneous arc power. It is evident, therefore, that excessive speed of arc lengthening, either by magnetic looping

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Figure 1. 115-kv oil circuit breaker rated 1,500,000 kva with five-cycle interrupting time

Oil volume reduced to only 60 per cent of superseded eight-cycle breaker by using multiflow deion-grid interrupters

Figure 2. Cut-away view of 138-kv multiflow deion grid showing oil flow produced by upper pressure-generating arc

Lower arc is subjected to deionizing flow from three pairs of converging oil jets. Gases are exhausted through two pairs of vents at intermediate levels

of the arc, blasting of the arc through ports or around splitter plates, or by extremely high contact velocities, will tend toward raising the pressure peak and, therefore, influence the ultimate short-circuit capacity. Those arc rupturing devices which are relatively freely vented, avoid unnecessary arc lengthening, and utilize moderate contact opening speeds, will be most suited to application in circuit breakers of maximum interrupting rating.

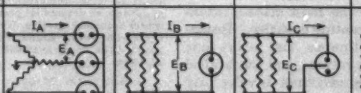
Although the effectiveness of modern circuit-interrupting devices has resulted in making the tank diameters of the high-voltage breakers more dependent on insulation clearances than on interrupting capacity, there are still certain considerations of physical dimensions which must not be neglected in the design of breakers having rupturing capacity as high as 5,000,000 kva. In the first place, the gas vented from the arc-extinguishing structures momentarily substitutes a weaker dielectric for the oil usually maintained between live parts and the grounded tank and also between the live parts on adjacent terminals. Insulating shields on the interrupting structures, and possibly insulating tank liners, can be used to maintain adequate dielectric strength, both by the introduction of the solid dielectric and by the baffling effects which maintain a layer of relatively undisturbed oil adjacent to the metal parts where the voltage gradient is a maximum. Well-rounded metallic shields covering all live parts are of particular benefit in keeping down excessive localized voltage gradients from which breakdown streamers might start.

Sufficient air space is usually provided above the oil level in the large breakers so that even if all exhaust pipe openings were closed the amount of gas generated during a maximum kilovolt-ampere interruption would raise the static pressure only a fraction of an atmosphere. However, circuit-breaker tanks are known to have a tendency to jump during heavy short-circuit interruptions due to transient pressure effects. These have been analyzed[3] and shown experimentally to be due to unbalanced vertical forces. As the gas is rapidly expelled from the arc-extinguishing structures, a considerable mass of oil must be lifted to make room for the expanding gases. A strong downward pressure impulse is transmitted to the bottom of the tank whereas the upward force is utilized in accelerating the moving oil mass and is not directly applied to the breaker structure. As a result, the entire breaker moves downward by elastic deformation of mounting supports, frame, and foundation, and then rebounds upward.

It is doubtful whether in the larger circuit breakers the upward moving oil strikes the cover or dome with sufficient force to produce appreciable mechanical pressure. Pressure records taken at the bottom of the tank indicate repeated pressure impulses due to oscillations of

Figure 3. Circuit-breaker test connections and equivalent three-phase interrupting capacity obtainable

Half-pole test and three-phase test on single pole assumes equal division of voltage between halves of pole unit under normal conditions

	A THREE POLE TEST	B SINGLE POLE TEST	C HALF POLE TEST	D 3φ ON 1 POLE TEST
TEST CIRCUIT				
TEST KVA	$\sqrt{3}\,E_A I_A$ *	$E_B I_B = \frac{E_A}{\sqrt{3}} I_B$	$E_C I_C = \frac{E_A}{2\sqrt{3}} I_C$	$\sqrt{3}\,E_D I_D$ *
EQUIVALENT 3φ KVA AT VOLTAGE E_A	$\sqrt{3}\,E_A I_A$	$3 E_B I_B$	$6 E_C I_C$	$6 E_D I_D$ *
EQUIV. 3φ KVA / 3φ LAB. CAP	1.0	1.8 +	3.6	3.46

* MAXIMUM CURRENT IN ANY ONE PHASE
+ BASED ON SINGLE-PHASE LABORATORY CAPACITY, 60% OF THREE-PHASE CAPACITY
* BASED ON SIX TIMES MAXIMUM DUTY ON HALF POLE

Figure 4. Two 60,000-kva high-power laboratory generators capable of producing three-phase short circuits of more than 2,000,000 kva at 13,200 volts

Each rotor weighs approximately 250 tons

the oil mass continuing for an appreciable time following arc interruption. In fact, the collapse of the gas bubble due to cooling immediately after arc rupture often results in a pressure impulse to the bottom of the tank at the moment of downward return of the oil mass which is actually of greater magnitude than the initial rise of pressure during arcing. Because of the pressure shocks on the breaker, it is well to have the tanks bolted firmly to the foundation. However, it has been found that the design of more effective arc-rupturing devices with resulting lower pressure impulses has more than kept up with the increase in breaker ratings so that stresses during the interruption of 3,000,000 to 5,000,000 kva in modern breakers are actually less than when interrupting 1,000,000 to 2,500,000 kva in the earlier designs.

The multiflow deion grid for high-voltage oil circuit breakers has been described before the Institute in previous papers.[3,4] The high degree of arc-rupturing effectiveness obtained with those interrupters has made possible a very substantial reduction in tank diameter and oil volume for standard ratings. For instance, the 1,500,000-kva breaker for 115-kv service shown in Figure 1 uses tanks only 50 inches in diameter with an oil volume 60 per cent of the breaker which it supersedes. It may be well to review the features which make the multiflow grids particularly suitable for circuit breakers of high rupturing capacity.

A cross section of a 138-kv five-cycle grid assembly which has been tested to nearly 5,000,000 kva is shown in Figure 2. The upper contact gap for producing oil-driving pressure is opened slightly in advance of the main contact gap by downward movement of the spring-biased intermediate contact and the main moving contact and cross bar. The oil under pressure flows toward the main arc through three pairs of inlet channels at different levels, passing through orifice openings in close proximity to the arc which is thereby cooled and deionized. The carbonized oil and arc products are then exhausted through two pairs of ports alternated between the inlet passages. By this means, the complete length of arc is acted upon, and arc rupture is accomplished without unnecessary lengthening and with surprisingly low pressure within the main body of oil, even at the highest short-circuit interrupting duty.

Even for three-cycle interrupting time ratings it has been found necessary to provide only two interrupting units per pole, the additional speed being obtained by faster tripping of the breaker mechanism and by increasing the speed of opening of the lower contact in the grid with a multiplying linkage. By eliminating extra pairs of multibreaks within the breaker, the total arc length, arc energy, and resulting pressure are kept within reasonable limits. The arcing time is so short that the silver tungsten arcing tips show relatively small amount of wear and burning during even the heaviest short circuit. Furthermore, the principle of bringing oil radially inward from opposite sides of the arc tends to center the arc in the orifices which are, therefore, protected by flowing oil from burning, and thus maintain their original dimensions very closely for a large number of short-circuit interruptions.

Validity of single-phase testing demonstrated by same performance under two conditions

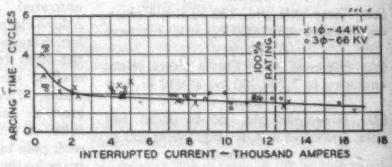


Figure 5. Comparison of arcing time on single-phase 44-kv tests and three-phase ungrounded 66-kv tests verifying 1,500,000-kva rating on standard deion grids

High-Power Laboratory Test Methods

Without a high-power testing laboratory, the development of modern circuit-interrupting devices to their present state of high effectiveness would have been virtually impossible. In the laboratory the voltage, current, and circuit conditions may be varied at will and repeated as often as necessary to obtain the desired amount of design and performance data.

Final verification of a new design by field tests on an actual power system has, of course, certain advantages both to the manufacturer and operating company, particularly where the short-circuit capacity available is in excess of that provided by the testing laboratory. Thus, a confirmation of the methods of extrapolation in laboratory testing is obtained while the operator gains assurance as to the operation he may expect on his particular system. It should be recognized, however, that because of hazards involved in subjecting a power system to these heavy short circuits, the number of repeated tests necessarily is rather limited. Also, the low recovery rate usually associated with an extensively interconnected system makes it unlikely that the most severe circuit conditions to which the breaker might be exposed, perhaps in other locations, will be obtained during the tests.

Four methods of high-power laboratory testing applicable to high-voltage oil circuit breakers are illustrated in Figure 3. Method *A* is the standard three-phase connection from the power transformer bank to the test breaker with the fault ungrounded. This is rarely used for verifying the large outdoor floor-mounted oil circuit breakers which are tested more conveniently single phase, and which, in general, have ratings exceeding the three-phase short-circuit capacity of the laboratory. For instance, the two 60,000-kva testing generators of the Westinghouse High-Power Laboratory,[5] shown in Figure 4, will develop together a three-phase first-cycle symmetrical short circuit of over 2,000,000 kva at the generator voltage of 13,200 volts. However, the impedance of the step-up transformers limits the maximum three-phase short-circuit current at these higher voltages to 1,600,000 kva. By pretripping the test breaker so that the circuit breaker contacts will part in the first cycle of short circuit, the total rms current measured in the most asymmetrical phase will reach a value approximately 50 per cent greater than the symmetrical value. Calculating the

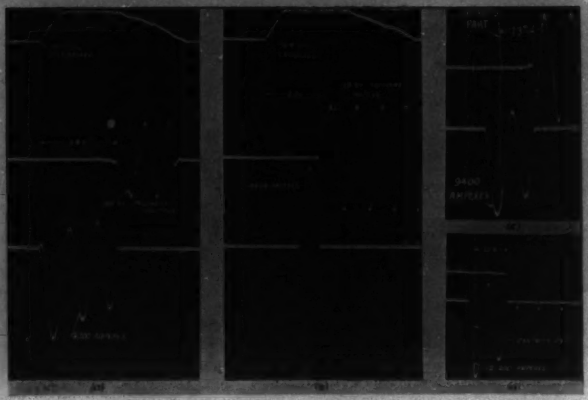


Figure 6. 230-kv multiflow deion-grid short-circuit tests

(a). Three-cycle grid, 198 kv single-phase equivalent to 2,500,000 kva at 230 kv three phase

(b). Three-cycle grid, 132 kv single phase, equivalent to 4,300,000 kva at 230 kv three phase

(c). Five-cycle grid, 132 kv single phase, equivalent to 3,700,000 kva at 230 kv three phase

(d). Three-cycle grid, 66 kv across half pole, equivalent to 4,800,000 kva at 230 kv three phase

three-phase kva on the basis of initial voltage and the maximum rms current in any one phase, the resulting short circuit may be considered to demonstrate an interrupting capacity of 2,400,000 kva. The shorter the arcing time, the more valid this test becomes, since the current decrement during the arcing period will be somewhat greater than under average power-system short-circuit conditions.

Method *B* of applying a single-phase fault at normal line-to-ground voltage to a single breaker pole is the most common method of laboratory testing of high-voltage breakers. With minimum transformer impedance obtained by paralleling all transformers, about 60 per cent of the three-phase capacity is developed in the single pole, the equivalent three-phase power, therefore, being 1.8 times the laboratory capacity. Thus, the two Westinghouse generators feeding six single-phase transformers in parallel will produce a first-cycle symmetrical single-phase short circuit of nearly 1,000,000 kva, corresponding to a three-phase grounded fault of 3,000,000 kva. Pre-tripping to obtain greater asymmetry during the arcing period will raise the equivalent three-phase power to well over 4,000,000 kva.

The question often is raised in connection with single-phase tests at line-to-ground voltage as to whether the adequacy of a breaker to interrupt a three-phase ungrounded fault has been demonstrated. In the latter case, the first pole to clear must interrupt 87 per cent of line voltage instead of 58 per cent, while the other two poles divide the duty in opening the line-to-line fault which remains. The discrepancy is not nearly so great as might be imagined, however, since, on a three-phase ungrounded test, each pole takes its turn in succession to try to be the first pole to clear the circuit. This follows from the fact that the currents in each of the three phases do not go through zero value at the same time but at approximately 60 electrical degree intervals. Failure to perform satisfactorily actually would mean that no one of the three poles had the ability to open the short-circuit current at 87 per cent of line voltage. It is not surprising, therefore, that a test at this 87 per cent voltage applied directly to a single breaker pole, which has no choice but to clear or fail, should impose a more severe condition than a three-phase ungrounded fault on the full three-pole breaker. For this reason, a circuit breaker which has been demonstrated to have the ability to interrupt short circuits of at least moderate power at 87 to 100 per cent of line voltage may be tested single phase at 58 per cent of line voltage up to its rated interrupting current with considerable assurance of demonstrating the ability of the breaker to handle not only grounded short circuits but three-phase ungrounded short circuits as well.

Confirmation of this analysis is given by the test data plotted in Figure 5 showing the arcing time in a 69-kv oil circuit breaker being tested for a 1,500,000-kva rating by both single-phase tests at 44 kv and three-phase ungrounded tests at 66 kv. The average arcing time was almost identical under the two test conditions which were carried to short-circuit currents well above the breaker rating.

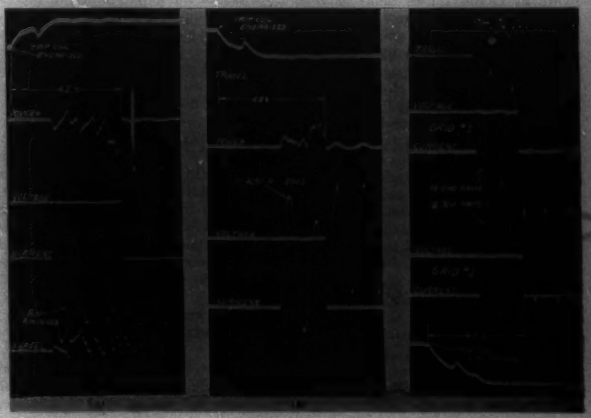
To demonstrate interrupting capacity at still higher kva, at least two other methods are available. By cutting out one half of the interrupting elements in a single pole as shown in method *C* of Figure 3, and testing at one-half line-to-

Figure 7. 138-kv multiflow deion-grid short-circuit tests

(a) Five-cycle grid, 88-kv single phase, equivalent to 4,200,000 kva at 152 kv three phase

(b) Five-cycle grid, 132-kv single phase, equivalent to 4,500,000 kva at 230 kv three phase

(c) Five-cycle grid, 44 kv across each grid, equivalent to 4,800,000 kva at 152 kv three phase



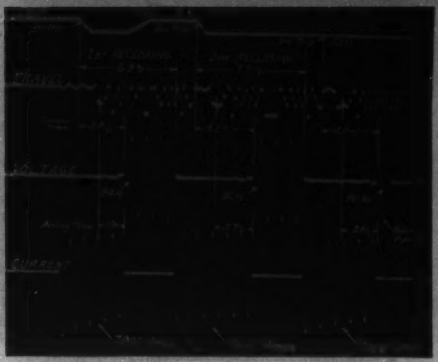


Figure 8 (above left). 35-cycle reclosing duty on 161-kv multiflow deion grids

Interruption of 12,200 amperes at 88 kv to ground, equivalent to 3,200,000 kva three phase, reclosed in 29.5 cycles, second interruption of 9,500 amperes. Both operations within three cycles each

Figure 9 (left). 20-cycle reclosing duty on 161-kv multiflow deion grids

Interruption of 11,100 amperes at 88 kv to ground, equivalent to 2,900,000 kva three phase, reclosed in 20 cycles, second interruption of 10,000 amperes. Both operations within four cycles each

Figure 10 (above right). Eight-cyle double reclosing duty on 161-kv multiflow deion grids

Three interruptions averaging 7,500 amperes at 88 kv to ground, equivalent to 2,000,000 kva three phase, reclosed in 6.9 and 7.7 cycles. All operations within five cycles each

ground voltage, it is theoretically possible to subject the half pole to twice as much duty as would be the case when testing the complete pole unit. However, this test may be deficient in three respects. In the first place, the voltage distribution at the time of interruption is such that more than half of the recovery voltage appears across one of two breaks in a grounded steel-tank breaker. In the second place, the voltage between the energized terminal and the tank under this special test condition is only one half of normal and, therefore, the possibility of flashover through gas bubbles is not adequately checked. In the third place, the total stress on the pole unit with regard to physical shocks and total volume of gas produced is only one half the value to be expected with the whole pole unit functioning at full power.

The question of voltage distribution can be minimized if some controlling means such as a suitable resistor is used across each of the interrupters so as to assure a substantially equal division of voltage between the two halves of the breaker. Then, insofar as the ability of the half pole to interrupt its rated voltage and current is concerned, this type of test may be considered valid.

The fourth test method, connection *D* of Figure 3, of applying a three-phase short circuit to the single-test pole unit has been used in European high-power laboratories for many years.[8] Two phases from the power transformers are connected to the main terminals and the third phase grounded and connected by a flexible shunt inside the breaker to the moving contact cross arm. Line-to-line test voltage is thus applied to each half of the pole unit, although it should be recognized that the currents are out of phase and also that the first pole to clear only gets 87 per cent of the value which the second pole clears. Nevertheless, this test has the advantage of developing the full amount of arc energy in the single-pole unit. Also, the electromagnetic stresses and the expulsion effect on the tip of the moving contact are more equally balanced. Instead of calculating the equivalent three-phase short-circuit duty as three times the three-phase laboratory output, it seems reasonable to apply the same criterion used in method *C* of six times the maximum duty on the most highly stressed half of the pole unit which gives a three-phase equivalent factor of $6\sqrt{3}$, or 3.46.

Short-Circuit Tests Above 3,500,000 Kva

A number of very high power interruptions have been made during the development and verification of high-voltage breakers for 3,500,000 kva using the test methods outlined here. For instance, the three-cycle 230-kv breaker for 3,500,000 kva was given a single-phase test at normal line-to-ground voltage of 132 kv interrupting a total asymmetrical current of 10,900 amperes. This is a direct test of 1,440,000 kva on the single test pole, equivalent to4,300,000 kva three phase. As a further check on the interrupting ability of this breaker, 87 per cent of line voltage or 198 kv was applied to the single-pole unit, and a short-circuit current of 6,300 amperes cleared satisfactorily. This is equivalent to 2,500,000 kva on the basis of current alone, but if the 50 per cent additional voltage is included, the equivalent kva for a three-phase short circuit on a 345-kv

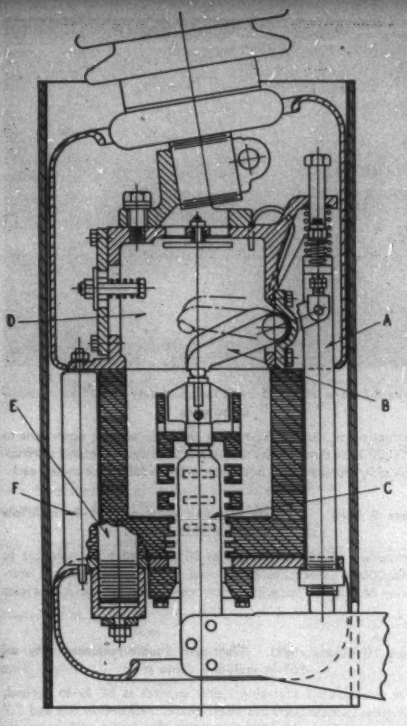


Figure 11 (left). 5,000,000-kva multiflow deion grid design for five-cycle interrupting time

Side operating rod *A* opens upper contact *B* simultaneously with opening of main contact *C*. Large oil reserve in pressure chamber *D*; strong tie rods *E*; resistor *F* for voltage distribution control

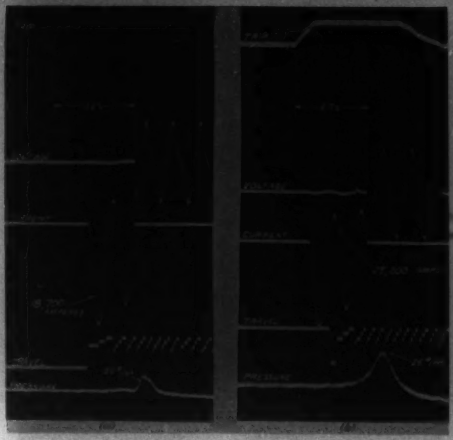


Figure 13 (above). High-power interrupting tests on multiflow deion grids using half-pole test method

(a). 230-kv interrupter, 18,700 amperes at 66 kv across half pole, equivalent to 7,400,000 kva three phase
(b). 161-kv interrupter, 25,200 amperes at 44 kv across half pole, equivalent to 6,600,000 kva three phase

system may be considered to be 3,750,000 kva. A still higher current of 12,200 amperes was interrupted with one half of the pole unit shunted out and 66 kv applied to the other half. Assuming that all six similar units of the complete three-pole breaker were handling the same duty, this would be equivalent to 4,800,000 three phase kva.

A design of 230-kv five-cycle multiflow grids was tested up to 9,400 amperes with 132 kv across the single pole, which is a direct test equivalent to 3,700,000 kva. The oscillogram for this test and the three 230-kv tests mentioned in the previous paragraph are shown in Figure 6.

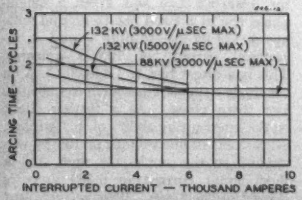


Figure 12. Arcing time in high-voltage multiflow deion grid fairly constant over wide range of voltage, interrupted current, and voltage recovery rate

Although 138-kv breakers could be tested at the line-to-ground voltage of 76 kv, maximum power can be obtained at the standard laboratory test voltage of 88 kv, and the slightly higher voltage demonstrates some additional factor of safety and voltage-interrupting ability. Three high-power tests are shown in Figure 7 on a 138-kv breaker. The maximum current of 15,800 amperes at 88 kv corresponds to 3,800,000 kva at rated voltage and 4,200,000 kva at the actual test voltage. The exceptional interrupting ability of this particular multiflow deion grid was demonstrated by interrupting the maximum capacity of the laboratory with full-line voltage across the single pole. This test of 11,400 amperes with 132 kv on a single pole was interrupted satisfactorily, being actually equivalent to a 230-kv three-phase short circuit of 4,500,000 kva. A three-phase short-circuit test applied to the single pole with 44 kv across each grid also was obtained, clearing 18,300 and 15,500 amperes in the two interrupters. For this test, the short-circuit power on a three-phase basis at rated voltage corresponds to 4,800,000 kva.

Ultrahigh-Speed Reclosing

The value of high kilovolt-ampere laboratory interrupting capacity test is unusually important in the case of high-speed reclosing. Under these conditions, the gas generated from the first operation might be expected to produce conditions that would affect the interrupting ability on a succeeding operation after an interval as short as 20 or 30 cycles. It is, therefore, very hazardous to extrapolate from low-kva tests on high-speed reclosing duty cycles to estimate the interrupting ability at high kva. It has been found that the multiflow deion grids are readily applied to ultrahigh-speed reclosing duty cycles, as illustrated in the following examples of tests made with a 161-kv five-cycle multiflow grid design.

The first test illustrated in Figure 8 is an interruption of 12,200 amperes at 88 kv across the single pole on a 35-cycle reclosure which corresponds to an interrupting duty of 3,200,000 kva. With the timing altered to give a 20-cycle reclosing operation, the next film in Figure 9 illustrates the interruption of 11,100 amperes at 88 kv across a single pole.

During an experimental test aimed at

approximately ten-cycle reclosing, a double reclosure was obtained with only seven to eight cycles for the reclosing intervals as shown in Figure 10. The current cleared was 7,900 amperes at 88 kv, corresponding to a three-phase fault of 2,100,000 kva, and, in spite of the extraordinarily heavy duty of three operations at such close intervals, every interruption was accomplished within five cycles and the external demonstration on the breaker did not appear much greater than was to have been expected on a normal 20-cycle reclosing duty. This test gives evidence of a large factor of safety in interrupting ability of the multiflow deion grid, both for standard interrupting operations and for high-speed reclosing duty cycles. It has become evident that, while the interrupting capacity is reduced by very rapid reclosing operations, there is no inherent limitation on the rapidity with which a circuit breaker can be reclosed and interrupt a second fault. With such an effective circuit interrupter, the design problem becomes one of providing an adequate mechanism and control scheme for these rapid duty cycles. The real limit will be set by the minimum time which must elapse after the first interruption for deionization of the line flashover to avoid re-establishment of the fault when voltage is reapplied, unless the fault is permanent.

A 5,000,000-Kva Circuit-Breaker Design

As a result of confirmation gained from these and many hundreds of other high-power laboratory tests on a variety of high-voltage circuit interrupters, some showing good performance and others failing completely, the principal design features of a high-voltage oil circuit breaker capable of meeting an interrupting capacity rating of 5,000,000 kva have become fairly clear. With substantially constant arcing time in the high short-circuit current range, the gas generation and tank pressure become almost directly proportional to interrupting rating. This means that the tank volume should be increased in proportion to the rating in order to keep adequate electrical clearances during arc rupture. Other than an increase in the size and strength of the steel tanks, there need be relatively few differences in the main structural features as compared to present day 2,500,000- and 3,500,000-kva designs.

The heart of the circuit breaker is, however, the arc-extinguishing device. Figure 11 shows a sectional view of a multiflow deion grid designed for a 5,000,000-kva rating with five-cycle interrupting time. The four insulating tie rods have been increased in strength and the volume of the upper pressure chamber enlarged substantially. This assures a sufficient quantity of oil for high-speed reclosing where the interval between operations is too short to permit refilling. No appreciable change is required in the interrupting section other than a slight increase in size of the fibre plates to accommodate the large tie rods. The resistor of about $1^1/_2$ megohms connected between the top and bottom of the stack assures approximately equal division of voltage between the pair of interrupting units in each pole of the breaker.

The suitability of the multiflow deion grid interrupters for extrapolation to higher powers is shown by the characteristic curves of Figure 12. The arcing time, particularly at the higher currents, is very nearly the same for tests at voltages of either 88 kv and 132 kv. Also, a change in voltage-recovery rate of two to one made only a slight change in the arcing time, indicating positive arc-interrupting action.

In order to determine the arc-rupturing performance at extremely high currents, the half-pole test method was applied to experimental units of a design similar to Figure 11, one built for a 230-kv five-cycle rating and one for a 161-kv five-cycle rating. Oscillograms of two tests are shown in Figure 13, the first being an interruption of 18,700 amperes with 66 kv across one grid unit, this being one half the normal line-to-ground voltage for a 230-kv system. The corresponding three-phase short-circuit power is 7,400,000 kva. There was very little external evidence of this tremendous power being interrupted, the maximum impulse pressure being only 50 pounds per square inch. The laboratory circuit on which this test was made had the very high recovery rate of 3,100 volts per microsecond. Test *B* of Figure 12 was made with 44 kv across a single 161-kv grid unit, corresponding to one half the line-to-ground voltage for a 154-kv system, the circuit-voltage recovery rate being 2,500 volts per microsecond. The interrupted current of 25,200 amperes amounts to 6,600,000 kva on a three-phase basis.

These and other tests indicate that 5,000,000-kva ratings for high-voltage oil circuit breakers equipped with multiflow deion grids are entirely practical.

Conclusion

By utilizing special high-power laboratory test methods such as the application of short circuits to only one half of a single breaker pole, sufficient information has been obtained concerning the performance of modern oil circuit breakers to indicate interrupting ability considerably above present ratings. Certain high-speed reclosing breakers have been shown apparently to have no inherent limitation in the shortness of the time interval between successive operations, although there is some reduction in interrupting capacity. The accumulation of considerable short-circuit test data at very high powers on high-voltage oil circuit breakers equipped with multiflow deion grids gives considerable assurance that, when needed, circuit breakers having ratings of 5,000,000 kva can be made available.

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Vibration Insulation and Structural Rubber

J. A. CONNON
NONMEMBER AIEE

SENSITIVE electric and electronic devices are what might be termed the "nerve centers" of modern war equipment. The men in airplanes, ships, and tanks depend upon them for communication, for fire and direction control, and for the detection of enemy targets. The role of these devices in nonmilitary applications is familiar.

To ensure accurate functioning and prolonged life, these units must be protected from damaging vibration and shock. It is the purpose of this paper to present to the engineer concerned with the protection of delicate equipments a compilation of information, on the fundamentals of mechanical vibrations and the properties of structural rubber, which otherwise could be obtained only through critical study of a large volume of existing data.

Vibration is, in general, a periodic motion essentially sinusoidal in character. It is practically always objectionable and its elimination or insulation is desirable. The term vibration elimination, it is to be borne in mind, is not synonomous with vibration insulation. Vibration elimination connotes correction of the condition causing vibration, whereas vibration insulation deals with diminishing the amount of transmitted vibrational energy.

Vibration-insulation problems can be classified in two categories:

1. Problems involving the insulation, from its surroundings, of a unit originating vibratory disturbances, for example, an airplane engine.

2. Problems involving the protection of a delicate unit from external vibratory disturbances, for example, a radio set, an instrument panel.

Problems in either category can be solved by supporting the unit on a correctly designed, resilient suspension. Rubber mountings, or rubber springs as they are in reality, are used extensively for this purpose; they are both practical and economical.

Requisite to the proper appraisal and solution of vibration-insulation problems is an understanding of the fundamentals and theory of mechanical vibrations.

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J. A. Connon is product engineer, war products division, United States Rubber Company, Los Angeles, Calif.

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Fundamentals of Mechanical Vibrations

Consider a system consisting of a mass supported on a spring and constrained by guides so that only vertical movements are possible (Figure 1). A mechanical system of this sort, the geometrical position of which can be expressed at any instant by one number only, is said to have one degree of freedom. Assume that damping is absent and that the spring deflects according to Hooke's Law (within the elastic limit of any body the ratio of the stress to the strain produced is constant).

The deflection of the spring due to the weight of the mass is known as the *static deflection* (d). If the force required to deflect the spring a given amount is relatively great, the spring is said to be "stiff." Spring stiffness is denoted by the *spring constant* (k) defined as the number of pounds required to deflect the spring one linear inch.

If the mass be displaced by a single push or pull and then released, it will oscillate in free vibration above and below its equilibrium position (the original rest point) at a frequency known as the *natural frequency*. The natural frequency of a spring system is a function of the static deflection.

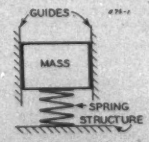


Figure 1. A single-degree-of-freedom system

$$f_n = \frac{188}{\sqrt{d}} \qquad (1)$$

f_n = natural frequency (cycles per minute)
d = static deflection (inches)

It can be seen immediately that high natural frequencies correspond with small deflections (refer "natural frequency versus static deflection" curve, Figure 2).

Assume now that the mass in Figure 1 is a machine in which a certain amount of unbalance exists. When the machine is running, it is acted upon by a vertical periodic force (deriving from the unbalance) which causes it to vibrate (a problem in category 1). This impressed force, one of three acting on the mass (the others are inertia force of the mass and the spring force) has a maximum value F and a frequency f_f. The vibration causes the already statically deflected spring alternately to be compressed and elongated a small amount below and above its equilibrium position, hence it exerts on, or transmits to, the supporting structure a force whose maximum value it can be shown is

$$X = F \frac{1}{1 - \left(\frac{f_f}{f_n}\right)^2} \qquad (2)$$

X = transmitted force
F = impressed force
f_f = impressed frequency
f_n = natural frequency

The ratio of the transmitted force to the impressed force is known as transmissibility.

$$\text{Transmissibility} = \frac{\text{transmitted force}}{\text{impressed force}} = \frac{X}{F} \qquad (3)$$

The ideal, of course, is to have transmissibility equal to zero (the practical aim is to make it as small as possible). It is evident that the value of transmissibility depends solely upon the relative values of the impressed and natural frequencies,

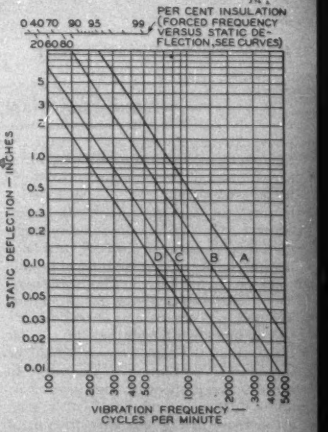


Figure 2. The relationship between natural frequency and static deflection, and per-cent insulation for various combinations of forced frequency and static deflection in an undamped, single-degree-of-freedom system

Curve *A*—Forced frequency versus static deflection for 93-per-cent insulation
Curve *B*—Forced frequency versus static deflection for 81-per-cent insulation
Curve *C*—Forced frequency versus static deflection for 0-per-cent insulation
Curve *D*—Natural frequency versus static deflection

and that, fundamentally, vibration insulation does not entail "absorption" of vibratory energy in the spring but is achieved through the "mismatching" of frequencies.

A plot of transmissibility against *frequency ratio* (f_f/f_n) is given in Figure 3. Examination of this curve reveals that when $(f_f/f_n) < \sqrt{2}$, the transmissibility is greater than unity. Theoretically, infinite transmitted forces (and displacement amplitudes) can occur at resonance ($f_f/f_n = 1$). Insulation, or reduction of transferred vibration, prevails only when $(f_f/f_n) > \sqrt{2}$.

The value of *per-cent insulation* is given by the following expression:

$$\text{Per-cent insulation} = (1 - \text{transmissibility}) \times 100 \quad (4)$$

The 0-, 81-, and 93-per-cent insulation curves in Figure 2 are plots of arbitrarily selected solutions of equation 4.

In the preceding section a system acted upon by a single external force and having only vertical motion was considered. The forces acting on, and the motions of, a real system are considerably more complex. A rubber mounting, too, is a more complex entity than a hypothetical spring chosen for the first illustration.

Imagine a device, such as a radio set, that must be mounted protectively in an airplane (a problem in category 2). Assume, for the sake of simplicity, that it is a rectangular mass whose center of gravity is located at its geometric center. Assume, too, that identical resilient mountings are installed under the set, one at each of the four base corners (Figure 4A). A unit mounted in this manner has six degrees of freedom, that is, six motions are possible at any instant: translational motion along each of three mutually orthogonal axes (for convenience these axes can be labelled X, Y, and Z, and considered to have their origin (O), at the neutral position of the center of gravity of the mass), and rotational motion around each of these axes.

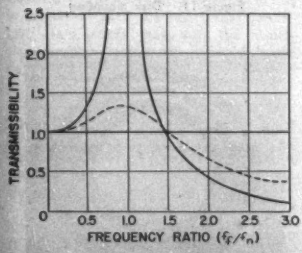
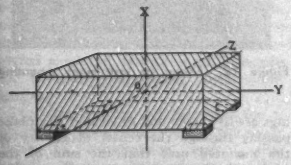
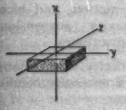


Figure 3. Values of transmissibility for various values of (f_f/f_n) in an undamped system (solid line); the effect of damping on transmissibility (dash line)



A—Diagrammatic representation of a mass mounted on springs



B—Diagrammatic representation of a rubber spring

Figure 4

Figure 7 (left). Cylindrical mounting

Figure 8 (right). Cylindrical mounting enclosed in safety cup

The motions of a mounted unit of given mass and moments of inertia are dependent upon:

1. Character of the excitation.
2. Elastic constants and damping of the mountings.
3. Location of the mountings.

In general, the vibratory forces at any location in a structure occur in several directions at different frequencies and with different amplitudes. These forces are both translatory and rotary in nature. The curves shown in Figure 5 are illustrative. They represent the translational-displacement components (simultaneously measured along three axes) of a rigidly mounted unit. (Displacements and accelerations rather than forces ordinarily are measured.) The data were taken from the study of a particular problem. It is to be noted that the vertical amplitude is considerably greater than either the athwartship or fore and aft amplitudes and that the fore and aft frequency differs considerably from the vertical and athwartship frequencies. A similar record (not shown) of the rotational displacements was made in this study.

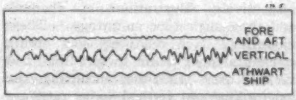


Figure 5. A record of the translational displacement components of a rigidly mounted unit

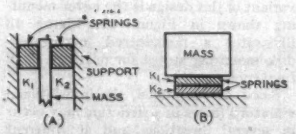


Figure 6

The characteristics of a structure have a great deal to do with determining the nature of the vibratory forces at any particular location. The principal frequencies usually are related, simply, to those of rotating or reciprocating mechanisms installed elsewhere in the structure. The amplitudes of, and the directions in which the vibratory forces occur are, in the general case, not in accordance with any simple relationship and are not readily predictable.

Attention now will be given to the elastic properties of rubber mountings. A rubber mounting (Figure 4B) can be considered to have three mutually orthogonal elastic axes, x, y, and z, the origin located at the neutral position of the point of application of the load. In the general case, the rectilinear elastic constants, or spring rates, along these axes are unequal. (The torsional constants around them, ordinarily neglected, are also unequal.) The relationship among the constants is dependent primarily upon the design of the mounting.

Since the elastic constants differ, the deflections corresponding to a given load applied successively along each axis will differ. A rubber mounting, therefore, for any given loading has three different, rectilinear, natural frequencies, one along each axes.

In a normal installation the load on a mounting is applied in the direction of one axis; the x axis, for example. The natural or resonant frequency in this direction can be calculated from the observed deflection. The coexistent resonant frequencies in each of the other directions can be computed by substituting for d in equation 1 the amount the mounting would deflect if the load, actually applied along the x axis, were applied successively along the y and z axes.

It is perhaps well to point out that if springs are combined in parallel (Figure 6A), or in series (Figure 6B), the com-

bined or over-all spring constants of the combinations are as follows:

In a parallel system

$$K = k_1 + k_2 + k_3 + \ldots k_n$$

In a series system

$$K = \frac{1}{\frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \ldots + \frac{1}{k_n}}$$

K = over-all spring constant

$k_1, k_2, k_3, \ldots k_n$ = spring constants of the individual springs

The deflections, hence the natural frequencies, of such combinations are functions of the over-all constant.

Figure 9. Safety channel mounting

Figure 10. Heavy-duty three-angle mounting

In any rubber-suspension vibration system there is a damping force which originates in the mountings and acts on the mass. The effect of this damping force is to prevent the build-up of large forces and amplitudes at or near resonance and to decrease the efficiency of mountings at frequency ratios greater than $\sqrt{2}$. Damping rounds off the peak of the transmissibility curve and moves it everywhere closer to the value one (Figure 3). The amount of damping, therefore, must be a compromise between the good low-frequency effects and the poor high-frequency effects. It is desirable ordinarily to have the minimum damping that satisfactorily will limit resonant vibration.

It must be remembered that the rapidity with which a mechanism is brought through resonances as its speed is changed has an influence on the amount of build-up. Restricting the operation at or near resonances to a short-duration transient obviously is recommended.

Several representative rubber mountings are shown in Figures 7 through 13. It will be observed that, to facilitate its application as an elastic support, rubber generally is adhered to metal. The mounting in Figure 7 is the simplest type; a cylinder of rubber with studs adhered to the ends. It can support a load in either compression, that is, normal to its ends, or in shear, parallel to the end planes. This type of mounting has relatively low spring rates in all directions parallel to the end planes. Figure 8 illustrates a refinement of this type incorporating a safety cup; it is designed to support a load in compression. It is well in most cases to arrange the rubber supports so that in case of complete failure of the rubber, due to accident or fire, the mounted unit still will be supported by some sort of interlocking metal device. Figures 9 and 10 are, respectively, illustrations of channel, and three-angle-type mountings. These mountings have relatively low spring constants along their longitudinal and vertical axes. In either mounting, the longitudinal and vertical spring rates are equal. An unusual disk-type mounting which has low and substantially equal spring rates along all three elastic axes is shown in Figure 11. A special-purpose variant of this design is the meter mounting shown in Figure 12. Figure 13 illustrates a nonadhered, corrugated-disk mounting suited for relatively high frequencies.

Since, as was stated, the translational vibratory forces in a structure may occur in several directions and at different frequencies, it is expedient:

1. To use mountings which provide the greatest deflections commensurate with stability.

2. To install mountings whose highest natural frequency is sufficiently far below the lowest expected impressed frequency, to ensure adequate insulation in all directions.

3. To install the "softest" axis or axes of the mountings parallel to the direction or plane in which the greatest disturbance occurs.

In a given excited system, the elastic constants of the springs, together with their disposition with respect to the neutral position of the center of gravity of the mounted unit and the moments of inertia of the unit, determine the frequencies at which rotational, or rocking, resonances occur. The distances of the mounts from the axes of the unit are the arms of the moments tending to produce angular motion about them. The moments of inertia of the unit express, of course, the rotational properties of the mass.

The calculation of the frequencies at which rocking resonances occur will not be dealt with in this paper. Suffice it to say that in most practical systems:

1. The frequencies at which the three rotational resonances occur are in the neighborhood of the translational resonances.

2. In general, their presence tends to extend the range of frequencies over which transmissibility exceeds a value of one. The accelerations arising from them can be as destructive as those related to translational resonances. Hence, their insulation or prevention is desirable.

3. If rotary excitation is negligible, the rocking modes ordinarily can be prevented by means of a symmetrical center-of-gravity suspension, that is, one in which the mountings are so chosen and so located in a plane passing through the center of gravity of the mounted unit that the sum of the moments about the center of gravity, around the X, Y, and Z axes, equals zero. In such a system, translational excitation does not cause angular motion, and vice versa. A center-of-gravity suspension possesses, too, stability advantages.

4. In a noncenter-of-gravity suspension, rotary excitation is not a necessary condition for rocking.

Figure 11. Disk mounting

Figure 12. Meter or instrument mounting

5. In a noncenter-of-gravity suspension in which the mountings are located beneath the unit, diminution of the range over which rocking resonances occur can be achieved through the use of mountings having substantially lower elastic constants along horizontal axes.

An indication of the effects some of the factors just discussed can have on a system may be obtained from an examination of Figures 14, 15, and 16. The transmissibility curves in these figures were plotted from shake-table data. It can be seen that superior insulation was achieved in the case in which mountings having relatively-lower natural frequencies in the horizontal directions were used under the unit (Figure 15). Even more marked improvement in insulation was obtained when these same mountings were placed in a plane through the center of gravity of the unit (Figure 16).

It may be concluded that the best method of vibration mounting any type of unit is a center of gravity suspension on mountings, of suitable capacity, having equal and low natural frequencies along all three elastic axes.

Structural Rubber

The word "rubber" when used in this section refers to natural rubber.

The following information is primarily qualitative rather than quantitative. It is presented with the belief that familiarity, in a general way, with the properties of rubber compounds is helpful to the engineer concerned with the use of rubber mountings.

Rubber, when used as mechanical building material to support a load, is known as structural rubber. In this capacity it can be stressed in the following five ways: shear, compression, tension, torsion, and flexure.

It is to be noted that rubber, like water, is practically incompressible (Figure 17). It is said to be stressed in compression when supporting a load which tends to squeeze it.

Most vibration mountings are designed to be loaded in either compression or shear. Tension is not employed extensively, because a slight tear or cut in rubber stressed in tension can produce rapid failure. Torsion may be considered a special case of shear. Flexure can involve compression, shear, and tension.

The stress-strain relationships for a rubber compound are given by the shear (Table I), compression, and tension moduli. These moduli are not, strictly, constants. Because of this fact, and because of other properties of rubber to be described, calculations in accordance with the theoretical formulas given in the first part of this paper will be slightly in error when rubber is the spring material under consideration.

It is well to discuss "durometer" and its significance with respect to modulus. The durometer values of compounds of the type used in mountings range normally between 30 and 70. These values are ascertained by means of the Shore durometer (type *A*), an instrument which measures the hardness of a rubber surface in terms of the indentation produced in the surface by a small, flat-tipped, tapering needle subjected to a practically constant indenting force. The arbitrary scale of this instrument runs with increasing hardness from 0 to 100. The relationship connecting durometer hardness with modulus is at best only approximate. Although useful for roughly determining the modulus of a stock, durometer is strictly a measure of only local surface hardness. The moduli of a stock provide the more accurate statement of its load carrying, or structural characteristics.

Figure 13. Cup mounting

The shear deflection of rubber is inversely proportional to the shear modulus.

The compression deflection is a function of shape, expressed by area ratio, as well as of the compression modulus. The area ratio of a slab of rubber is the ratio of the load-bearing area to the area free to bulge. Slabs having high (2.50) area ratios deflect a smaller percentage of their thickness than slabs of the same compound having low (0.25) area ratios.

The moduli of rubber compounds vary small amounts with temperature and with the amplitude and frequency of impressed vibration as well as with the static strain to which the rubber is subjected.

At low temperatures rubber stocks stiffen. For a given compound the temporary changes in moduli due to chilling depend upon the chill temperature, the duration of the chill, and the strain during the chill. The temperature at which the moduli increase rather suddenly is generally between −40 degrees Fahrenheit and −60 degrees Fahrenheit, depending upon the compound.

At temperatures above 170 degrees Fahrenheit ordinary structural rubber compounds begin to soften. The effect of heat aging becomes pronounced and, under strain, rubber acquires a permanent set or deformation.

The static moduli decrease with increased strain.

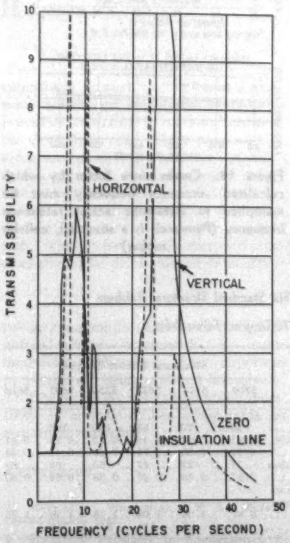


Figure 14. Shake-table performance of a unit mounted on rubber springs installed underneath the unit, the ratio of the horizontal elastic constants to the vertical was approximately 2:1

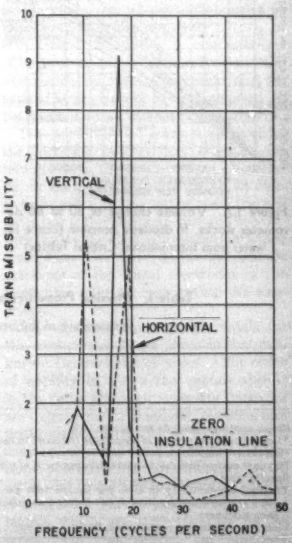


Figure 15. Shake-table performance of a unit mounted on rubber springs installed underneath the unit, the ratio of the horizontal elastic constants to the vertical was approximately 1:1

The moduli of rubber are greater for vibratory stress than for static (0 frequency stress). It is interesting to note that for mountings operating at low temperatures, the stiffness, and consequently the natural frequency, will be greater than that indicated by the increased static moduli alone, for the dynamic moduli are more sensitive to temperature changes than are the static.

For exact prediction of the natural frequency of a rubber mounting under load, the value calculated from the static deflection in equation 1 has to be adjusted. The frequency-factor curves in Figure 18 show the factor by which the calculated natural frequency should be multiplied in order to obtain the actual natural frequency. In most calculations this refinement can be neglected, particularly when dealing with the softer rubbers.

Damping is usually expressed as the ratio of the actual damping force, C, to the critical damping force C_c. The critical damping force is that force which is just sufficient to prevent oscillatory motion of a particular system when disturbed. The values of the ratio C/C_c for structural rubber compounds are in the neighborhood of 0.08.

Damping ordinarily limits the build-up of displacement amplitude at resonance to eight or ten times that of the impressed amplitude; it is possible for magnifications of from 15 to 20 to occur.

The damping forces exerted by rubber mountings derive from a property of the material known as hysteresis or internal friction. When rubber is deformed and allowed to return to its original position the load–deflection curve is not strictly a single line but a loop similar in shape to that shown in Figure 19. The area within the loop represents energy transformed into heat; "absorbed" by the mounting. This quantity is known as the hysteresis loss. Since rubber is a poor conductor of heat, its temperature will rise when it is excessively, repeatedly, and rapidly deformed.

Because of hysteresis, the amplitude of vibration of a system set into free vibration will become less with each successive oscillation. It has been found that each successive amplitude, measured on the same side of the equilibrium position, will be less than the former by a factor which is approximately constant

$$\frac{A_1}{A_0}=\frac{A_2}{A_1}=\frac{A_3}{A_2}=\frac{A_4}{A_3}\ldots\ldots=10^{-\kappa}$$

The quantity κ is called the logarithmic decrement of amplitude. Values for logarithmic decrement, successive-amplitude ratio, and per-cent energy loss due to hysteresis are given in Table I for rubber at 70 degrees Fahrenheit. These quantities decrease at higher temperatures.

When rubber is under load, there is a gradual increase in deflection which is referred to as drift. If the load is removed it is found that it has caused a permanent change in the unstressed dimensions of the rubber which is referred to as permanent set. Drift increases rapidly for a short time (a matter of hours) after the load is first applied and then the curve levels off to practically a horizontal line. The drift of rubber supporting a vibrating load will be greater than that for the same com-

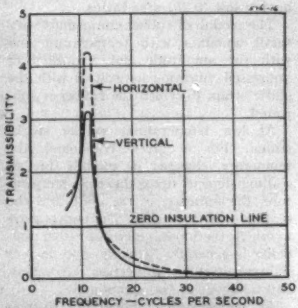


Figure 16. Shake-table performance of a unit mounted on rubber springs installed in a horizontal plane passing through the center of gravity; the ratio of the horizontal elastic constants to the vertical was approximately 1:1

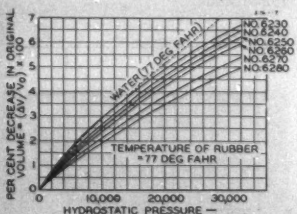

PER CENT DECREASE IN ORIGINAL VOLUME = (ΔV/V₀) × 100
WATER (17 DEG FAHR)
NO. 6230
NO. 6240
NO. 6250
NO. 6260
NO. 6270
NO. 6280
TEMPERATURE OF RUBBER = 77 DEG FAHR
HYDROSTATIC PRESSURE — POUNDS PER SQUARE INCH

Figure 17. Volume change of 30 to 80 durometer stocks, hydrostatic pressure (curve for water from International Critical Tables)

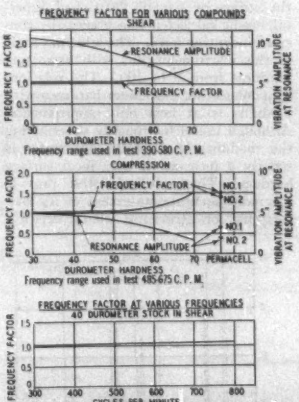


Figure 18. Curves show factor by which calculated resonance frequency must be multiplied to determine actual resonance frequency (Permacell is a structural, cellular rubber)

Table I. Physical Properties of Six Standard Structural Rubbers

Temperature of Rubber, 70 Degrees Fahrenheit

	Structural Rubber Number					
	5709	5133	5638	5255	5691	5623
Shear modulus, pounds per square inch	50	70	95	140	195	
*Logarithmic decrement of amplitude (referred to base 10)	0.041	0.055	0.14	0.23	0.35	0.47
*Successive amplitude ratio	0.91	0.88	0.72	0.59	0.45	0.34
Per-cent energy loss due to hysteresis, per cycle of vibration	17	22	47	65	80	89
Specific heat	0.47	0.43	0.40	0.38	0.35	0.33
Thermal conductivity in Btu, per square foot per hour for a temperature gradient of one degree Fahrenheit per inch thickness	0.97	1.04	1.08	1.15	1.26	1.33
Velocity of sound in rubber rods, feet per second	115	165	210	345	750	

* The logarithmic decrement given here represents the negative of the power to which 10 must be raised in order to obtain the ratio of any two consecutive amplitudes (on the same side of zero deflection) as unexcited vibration dies out. For instance, if the logarithmic decrement is 0.2, the ratio of one amplitude to the preceding one is $10^{-0.2}=\frac{1}{10^{0.2}}=\frac{1}{1.585}=0.631$ = successive amplitude ratio.

(Ordinarily logarithmic decrement is referred to Napierian log base e and, if such values are required, they would be 2.30 times the values given here.)

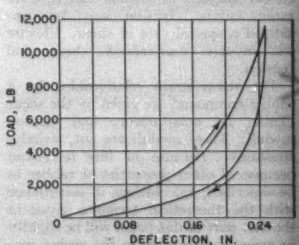


Figure 19. Hysteresis loop for a typical rubber compound

Electrolysis and Corrosion of Underground Power-System Cables

L. J. GORMAN
MEMBER AIEE

ELECTROLYTIC CORROSION is recognized universally as a major problem in the maintenance of underground metallic structures. This is particularly true in the case of underground cable and piping systems. The subject is of a primary interest to cable- and pipe-operating utilities, and a great deal of study and research is being devoted to electrolytic corrosion by utility engineers throughout the country.

The following is a summary of the principles and methods which are the outgrowth of long experience with the mitigation of electrolysis and corrosion on the power-system cables of the Consolidated Edison Company of New York, Inc. This system comprises approximately 22,000 miles of underground lead-covered cable operating under a wide variety of soil and duct conditions. Although system experience include both the cable and the gas-piping systems, this paper will deal more particularly with the conditions affecting the cable system.

Practically all of the essential factors involved in present-day problems of electrolysis and corrosion were recognized in the early work on this subject, and presented in the 1921 "Report of the American Committee on Electrolysis" and in other publications of that period.[1,2] In this earlier work emphasis was placed on electrolysis caused by stray electric currents, and little attention was given to the other factors influencing corrosion. During the past 15 or 20 years, the importance of these other factors, notably the influence of various galvanic or electrolytic cells which originate on the metal surface or in its environment, has been more clearly realized. Furthermore, a great deal has been added to our knowledge of the various corrosion processes and their control. Consequently, there has been a considerable change in point of view with respect to electrolysis, particularly in the evaluation of the various factors involved. This has led to important changes in the procedures for electrolysis testing and in the methods used for the mitigation of corrosion.

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L. J. GORMAN is assistant engineer in the electrical engineering department, Consolidated Edison Company of New York, Inc., New York, N. Y.

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Electrolytic Corrosion

It is well established that the corrosion of metal in the presence of moisture occurs extensively through electrochemical reactions which are essentially electrolytic processes occurring in various forms of the electrolytic cell. These processes are recognized as an important cause of widespread corrosion on underground structures and as constituting, in many instances, more serious problems than stray electric current or other forms of corrosion. The electrolytic-cell-corrosion processes should be distinguished from stray-current electrolysis where the source of current is external to the system. In the electrolytic cell the corroding current results from electrochemical reactions at the surface of the metal or in its immediate environment and is frequently referred to as galvanic corrosion. Like stray current, the electrolytic-cell processes involve the flow of electric current through an electrolyte and may be treated under the general subject of electrolysis.

The electrochemical theory of corrosion has been covered in detail in the numerous publications on that subject.[3,4,5,6,7] It is desired, however, to call attention to certain of the factors which relate more particularly to electrolytic corrosion of underground cable systems and which appear to have the most influence on the corrosion problems affecting the system under consideration.

Galvanic Potential and Current

In general the rate of corrosion in an electrolytic process depends on the magnitude of the current and the electrochemical equivalent of the metal. With the current densities and other conditions usually found in practice the rate of corrosion of metal may be calculated approximately by Faraday's law. The voltage has no effect on the corrosion except insofar as it determines the current strength. There is no minimum voltage below which electrolysis does not occur. Corrosion by electrolysis usually is localized and results in the characteristic pitting observed in the electrolysis of lead-cable sheath or iron pipe. The pitting is characteristic of both stray-current electrolysis and the electrolytic-cell type of corrosion, and the type of action cannot be distinguished by the appearance of the metallic surface.

The potential and current involved in the corrosion process may originate externally as in the stray-current electrolysis, or they may originate within an electrolytic cell. In the latter case, the cell potential is the algebraic sum of the voltages due to the electrode potentials which result from the relative anode and cathode reactions of the metal electrodes in the particular solution constituting the electrolyte.

The standard electrode potentials for the various metals are given in the well-known electrochemical series. The order of nobility in which the metals appear in the series and their values of potential are determined in standard solutions and under standard conditions which are not usually obtainable in practice. Electrode potentials vary considerably in soil water and frequently the order of nobility is reversed. This is particularly true of metals which are near together in the series. For this reason, the standard electromotive-force series is not directly applicable to the corrosion of metals in contact with soil moisture. The electrode potentials of various metals in sea water have been determined.[8]

pound supporting a static load at the same temperature. Drift is greater for severe vibration than for mild vibration; it is greater at high temperatures than at low.

The failure of a rubber mounting, in time, partly is due to the fact that the rubber member is under load during service and partly is due to the fact that it is fatigued by vibration. The dynamic-fatigue life of a rubber part, defined as the total number of repeated cycles of vibration required to rupture it, is dependent on the initial strain, the amplitude of vibration, the temperature of the rubber, the ingredients and state of cure of the rubber, and external destructive variables such as sunlight, ozone, and oil.

Since, at the present time, synthetic-rubber compounds must be substituted for natural-rubber compounds in some mounting applications, their structural properties are being explored intensively. To date they have not exhibited the versatility of natural-rubber compounds as structural materials.

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The potential of an electrolytic cell occurring on the surface of a metal in contact with an electrolyte will vary, depending on the condition of the surface, impurities, mechanical strains, and so forth which result in the formation of local cells. If uniformly distributed and closely associated, these cells tend to neutralize each other. Furthermore, the potential of a given metal will vary in different solutions or with different ion concentrations in the same solution. Galvanic potentials also may be produced by differential aeration, that is, by variations in the supply of oxygen to adjacent parts of the same metal surface. This type of cell may occur, for example, in a cable duct where the degree of aeration varies from point to point in the duct because of the accumulation of mud or sediment, or in a congested cable system where the supply of air to the cables in the bottom ducts is more or less restricted. Under these conditions the metal surfaces to which the oxygen supply is restricted will be anodic to the surfaces that are better aerated. Dissimilar metals and dissimilar soils are included as important sources of galvanic potential.

The potentials resulting from such causes as differential aeration, concentration cells, mechanical injuries, and so forth are local in character and usually small, ranging from a few hundredths of a volt to 0.1 volt or 0.2 volt in severe cases. These potentials do not cause serious corrosion under favorable duct conditions. However, severe corrosion has been experienced in ducts where the resistance to the corroding current is low. These local cells may be expected in any duct. Their activity will depend on the duct conditions.

The potentials caused by variations in the soil external to the duct bank may be considerable, depending on the relative characteristics of the soils concerned. For example, anodic potentials amounting to from 0.8 to 1.0 volt have been obtained between the cable sheath and the duct wall, where the duct bank passed through cinder-filled soil. These potentials may be local or extend over a considerable section of the duct bank and may cause severe corrosion in ducts where, otherwise, the conditions are favorable. It is important to distinguish between the purely local type of cell and the type of cell resulting from differences in the characteristics of relatively large masses of soil in which ducts are laid.

Electrolytic cells of the dissimilar-metal type frequently occur between the cable sheath and copper bond wires or bronze splice filling nipples, phase tags, and so forth. Serious local corrosion of the lead sheath may occur where cables with these attachments are exposed to manhole water, or where the sheath and attachments are in contact with wet cement or other covering used to protect the cables. Severe cases of galvanic corrosion have been experienced in water-filled manholes between the lead sheath and zinc-coated oil reservoirs and galvanized manhole hardware. The zinc is anodic to lead, and, when immersed in water with a large quantity of lead, the galvanic action removes the zinc, thus exposing the iron to natural corrosion. Numerous cases of galvanic corrosion of lead have been experienced in iron ducts because of galvanic potentials between the lead and rusted iron. In severe cases, potentials amounting to 0.4 volt have been measured between lead and iron rust to which the lead is anodic under the conditions usually found on the system.

Controlling Factors

In a corrosion cell of given open circuit, or static voltage, the current flow will depend upon a multitude of factors, such as polarization, relative anode and cathode areas, circuit resistance, film formation, passivity, hydrogen overvoltage, hydrogen-ion concentration (pH), oxidation, and other chemical reactions in the electrolyte. Some of the factors tend to retard the corrosion process and others tend to increase the corrosion cell activity.

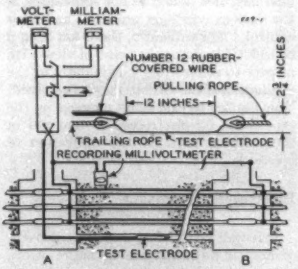

Figure 1. Method and equipment for surveying cable ducts

Of the several factors mentioned the most important in the control of underground corrosion appear to be polarization, hydrogen-ion concentration, circuit resistance and the relative anode and cathode areas. The rate of corrosion under most soil conditions appears to be controlled chiefly by the resistivity of the environment in contact with the cable and the rate at which hydrogen is depolarized or otherwise removed from the cathode areas.

Polarization is a general term used to group the various factors which influence the potential of the electrolytic cell with the passage of current. Polarization may include such factors as the effects of ion concentration at the electrodes, resistance changes resulting from the electrolytic processes, and certain electrode effects which depend on the composition and character of the electrodes. Polarization occurs, in varying degree, at both the anode and the cathode but usually is most pronounced at the cathode. When cathode polarization is predominant, the corrosion process is said to be cathode controlled, and, when anode polarization is predominant, the process is anode controlled. Hydrogen depolarization is effected by its combination with oxygen, or the hydrogen may be removed as a gas. Any agency tending to increase the oxygen available for depolarization will accelerate anode corrosion. Agitation of the electrolyte tends to increase the supply of depolarizing oxygen as well as aids in the removal of hydrogen gas bubbles.

The resistivity of the environment in immediate contact with the cable or pipe seems to be the principal factor in controlling cable-sheath and pipe corrosion. In the case of cable occupying ducts, the resistivity of the duct walls and any water or sediment contained in the duct will determine to a very large extent the amount of corrosion experienced on lead-covered cables. In practice, the contact resistance between the cable and its duct wall and through the duct wall may vary between wide limits in a single duct section, and the severity of the corrosion will be most pronounced at points of low resistance. In most cases a direct correlation has been found between this resistance and cable-sheath corrosion. The influence of duct resistance will be discussed further in another section of this paper.

In the usual case of cable-sheath corrosion, the major component of the resistance exists at the surface of the sheath, and any film formation that will increase this surface resistance is an important factor in controlling the corroding current. The use of certain chemical inhibitors, such as silicates, phosphates, chromates, and so forth, in the formation of protective films on lead sheath has been discussed by Radley and Richards[9] and other investigators. The protective effect of chemical inhibitors artificially applied to cable sheaths and ducts has not been investigated on the system of the Consolidated Edison Company. However, in the usual type of soil and duct water found on the system the natural formation of films does not appear to have any important influence on corrosion.

Wesley[10] has shown that the relative anode and cathode areas have an important influence on cathode polarization. If the cathode area be relatively large, the hydrogen polarization will be correspondingly weak, and anode corrosion will occur at a higher rate than under conditions where the cathode area is equal to or less than the anode area. This factor is of particular importance in selecting metals to be used together in sea water or soil. For example, in the selection of bolts or rivets the metal should be slightly ca-

thodic to that of the structure to which they are attached. Likewise, the solder used in cable splices should have as nearly as possible the same electrode potential as the lead sheath. The relative area effects are most pronounced where attempts are made to protect the cable sheath against dissimilar-metal corrosion by coating the sheath. Any imperfections in the coating will restrict the area of lead exposed and concentrate the corrosion. Furthermore, cement or other coatings used to arcproof cables appear to limit the relative area effect and to concentrate galvanic corrosion of the lead near the point of contact with the cathode metal.

A considerable amount of cable-sheath corrosion has been associated with alkaline soil and duct water. In most cases, the alkalinity is due to the presence of green concrete and frequently occurs in poorly drained ducts in which the accumulated duct water is evaporated slowly by the heat of the cables. This produces a concentration of the alkaline salts dissolved from the duct walls and surrounding soil, and pH values amounting to 11 or 12 have been obtained in severe cases. The action on the cable sheath appears to be chiefly chemical, producing the red or brown oxides of lead. In the usual case the action is aided by small positive potentials acting through a low-resistance electrolyte. In such cases the duct conditions can be improved by flushing the duct with fresh water. In manholes, the alkaline attack occurs most frequently under the cement arcproofing on the cables and splices where the protection used under the arcproofing is inadequate.

In further reference to hydrogen-ion concentration (pH) laboratory experiments indicate that soils having relatively high pH values are anodic to soils of lower pH and that cable passing from one type of soil to the other will tend to discharge current into the more alkaline soil. The potential differences appear to be approximately 0.06 volt for a difference of one in pH value, and the variation with pH seems to be a straight line function. These laboratory tests have been confirmed largely by field observations in which cables passing from a neutral or slightly acid soil into an alkaline soil have been found to be slightly negative with respect to the duct wall in the neutral or acid soil and definitely positive in the alkaline soil.

Stray-Current Electrolysis

The principles underlying stray-current electrolysis are too well known to require a further explanation at this time. The stray-current problem is mentioned, however, to call attention to the status of stray current as a factor in cable-sheath corrosion.

In Greater New York electrolysis from stray railway current has been reduced to minor proportions through the co-operative efforts of the several electric transit systems and the cable- and pipe-operating utilities concerned. However, the problem still exists, potentially, and to avoid serious consequences its control must be exercised through the continued supervision and maintenance of the various measures that have been installed for electrolysis mitigation. On the Consolidated Edison system this control is obtained through approximately 120 drainage connections to the railway negative returns at various locations throughout the area.

In certain parts of the territory the trolley service virtually has been discontinued, and many of the elevated-railway structures have been removed. The outstanding effect has been the removal of cathodic protection in sections where the rails and structures normally were positive with respect to the cable and piping

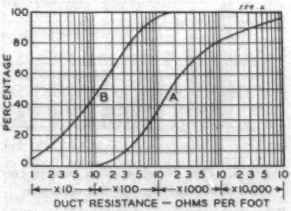

Figure 2. Cumulative percentage curves showing the results of duct-resistance surveys

A—Plotted from 9,500 tests at random locations on the system

B—Duct resistance associated with sheath corrosion

systems. In consequence, the electrolytic-cell type of corrosion has appeared in many localities formerly protected through cathodic action by the railway structures. Moreover the removal of the elevated- and street-railway structures has upset, to a considerable extent, the balance that formerly existed and has necessitated a major readjustment in many of the drainage connections and other measures used for protection in the anodic areas.

Cathodic corrosion has not been serious on the power-cable system in this territory. However, this type of corrosion is a matter of constant concern, and negative potentials are limited as much as possible, particularly in areas where the decomposition of sodium chloride or other salt and the deposition of their hydroxides on the cable sheath is likely to occur. Two or three severe cases of this type of corrosion have been experienced.

To date, there have been no cases of corrosion that could be identified with a-c electrolysis, although there are a number of single-conductor cross-bonded feeders operating on the systems with eight-to ten-volts alternating current from sheath to ground and 12 to 15 volts between sheaths of the phases. In some instances, the cables occupy ducts considered unfavorable, and some corrosion has been experienced. However, in all cases, this corrosion could be accounted for by small direct potentials or other duct conditions.

Electrolysis Surveys and Tests

The protection of the cable system depends primarily on the adequate supervision and control of all the factors involved and the maintenance of the measures adopted for the mitigation of electrolysis and corrosion. This supervision and maintenance is accomplished through systematically planned electrolysis surveys and tests which can be conveniently divided into three general classifications, namely,

1. Maintenance tests.
2. General surveys.
3. Special investigations.

Maintenance Tests. They are scheduled on a periodic basis to cover the inspection of existing installations for electrolysis protection and to check periodically the electrolysis conditions existing on the system. The installations include drainage connections, insulating joints, cathodic protection installations, and any other measures installed for electrolysis protection on either the cable or piping system. Usually maintenance tests are scheduled on an annual basis. Some installations such as those involving drainage switches, rectifiers, and other special equipment are inspected more frequently. In other cases where the conditions are well stabilized an inspection every two or three years is sufficient.

General Electrolysis Surveys. Made for the purpose of locating corrosion areas and obtaining general information on electrolysis conditions affecting the system, the general surveys may be supplemented by special tests to determine the protective measures to be installed in areas subject to electrolysis and corrosion. The general surveys are planned to cover systematically the various parts into which the system is divided for the purpose of survey. Consideration is given in particular to the localities in which changes in the electrolysis conditions are likely as the result of changes in the electric transit lines or important modifications in the cable system.

Special Tests. Made in situations which require a more or less extended investigation, frequently they involve the underground structures of other companies and may be initiated by either company depending on what structures are involved. The special work includes the investigation of the conditions

incidental to corrosion failures and the surveys and tests made in connection with important new cable installations.

Test Methods: The Duct Survey

The test methods employed for stray-current-electrolysis surveys have been fairly well standardized, and the test procedures are described in detail in the various publications on that subject.[1,2] In situations involving only stray currents, these procedures continue to give satisfactory results. However, the usual stray-current-electrolysis tests do not yield information on the local electrolytic-cell conditions existing between the test points because of the wide variations in the soil and duct conditions from point to point along the cable ducts. For this reason, other test methods are required for the electrolytic-cell types of corrosion. Considerable experimental work has been done to develop a test method that would yield test data that could be correlated with actual cable-sheath corrosion. This work has resulted in the present duct survey.

During the past ten years or more, the duct survey has been used on the cable system to explore the electrolysis conditions existing in duct sections between manholes, and particularly to investigate the duct conditions incidental to corrosion failures. The duct survey also is used to advantage where it is desired to explore the electrolysis conditions in ducts prior to the installation of new cable. Furthermore, statistical studies of a sufficient number of duct-survey data, obtained in connection with actual cable failures, will yield information and criteria which can be used as a basis for estimating the severity of particular electrolysis situations.

The duct survey is made by pulling an electrode through a vacant duct which is adjacent to the ducts carrying cable. Instruments are connected between this electrode and the lead sheath of the adjacent cables, and measurements of potential, current, and resistance are made at frequent intervals (five to ten feet) throughout the duct. The arrangement and connections for the test are shown in Figure 1. The test electrode most generally used consists of a piece of cable 12 inches long and 2.75 inches in diameter fitted with a pulling eye and test leads. A small galvanic potential may exist between the cable sheath and the test electrode, although the material in both is the same. This difference, however, is small (0.01 volt or less) and does not affect seriously the results. The surface of the electrode should be maintained in good condition, and its electrode potential with respect to cable sheath should be checked periodically using manhole or duct water as the electrolyte. Various nonpolarizing and other special types of electrode have been investigated. However, the most satisfactory results under the usual field conditions have been obtained with the short length of lead cable sheath. An essential requirement is that the electrode be as simple and as rugged as possible.

The potential existing between the duct wall and the adjacent cable sheath is measured by the voltmeter connection shown in Figure 1. A high-resistance voltmeter should be used to minimize the errors due to electrode-contact resistance. Voltmeters having a resistance of 400,000 ohms per volt or more are satisfactory for this purpose. Because of the high resistance of the voltmeter circuit, the potential of the test electrode will be substantially that of the duct wall, and the measurements thus obtained give an approximation of the potential of the cable sheath with respect to the duct wall from point to point through the duct. The potential survey is supplemented by a time record of potential taken at a selected point in the duct to determine

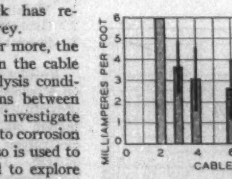

Figure 3. Age of cable versus average current discharged through test electrode

Data obtained in connection with corrosion failures

the characteristic of the potential. A 24-hour recorder, having a resistance of 10,000 ohms per volt, is used for this purpose. The characteristic of the record will indicate whether the condition is caused by an external source of potential, such as in stray-current electrolysis or by electric-cell conditions set up by variations in the environment.

To determine the magnitude and direction of the current picked up from or discharged to the duct wall through the test electrode, a low resistance milliammeter is connected in place of the voltmeter. Since the resistance of the milliammeter circuit is relatively low, the potential of the test electrode will be substantially that of the adjacent cables, and it may be assumed that the current discharge per foot of cable at the point of test is approximately in the same order of magnitude as that measured. This current, when flowing into the duct wall, will cause anodic corrosion, and it may, when flowing to the cable sheath, result in cathodic corrosion.

In the measurement of potential or current at points within the duct it is important to correct for the *IR* drop due to any stray current flowing on the cable sheaths. Where the cables are carrying appreciable stray current, for example, from manhole *A* to manhole *B* in Figure 1, there will be a potential drop along the sheath, and a reading taken at some mid-position in the duct and referred to the sheath in manhole *A* will not give an accurate reading of the potential and current at the point of test. To correct for sheath current the usual practice is to record the magnitude and direction of the current flowing on the sheath and to compute the *IR* drop to the point of test. The appropriate correction then can be applied to the readings of potential and current measured between the cable sheath and the test electrode. In most cases the *IR* drop between *A* and *B* can be measured directly by a recording millivoltmeter as shown in Figure 1.

The resistance between the test electrode as one terminal and the adjacent cable as the other is measured at each test point as a part of the survey. The measurement can be made conveniently by connecting a low-voltage battery (1.5-volt dry cell) in series with a sensitive milliammeter between the cable sheath and the test electrode. The resistance is computed from the battery voltage and the measured current. The milliammeter should have a sensitivity in the order of 0.05 milliampere per division, and its resistance should not exceed two or three ohms. Suitable shunt resistances can be used to vary the range as required. The same instrument can be used for both the current and the resistance measurements. A reversing switch is required to reverse the potential on the test electrode to minimize any errors due to small d-c sheath potentials, polarization, or other effects. The battery current in this test is usually small and does not appreciably influence the battery voltage. However, it is a good practice to check this voltage from time to time during the progress of the survey.

The resistance as measured in the foregoing is somewhat arbitrary and is mostly the contact resistance between the surface of the electrode in contact with the duct and the duct wall and represents, approximately, the contact resistance per duct foot of cable. The area of contact will vary, depending on the duct conditions. In dry ducts the contact area will be small, whereas in ducts containing mud and water the contact may be an appreciable part of the total electrode area. The relation between contact area and resistance and its influence on the interpretation of the test data is explained in the following section. The resistance of the duct bank, the earth, and the contact resistance between the duct walls and the cable sheath in the occupied ducts also are included in the measurement. However, these resistances are relatively low compared with the electrode resistance and apparently do not appreciably influence the results.

In new installations, where it is desired

to explore the duct conditions prior to installing cable, or where cables are not available in the duct bank under test, the adjacent water pipe or other pipe or cable system can be used for a resistance survey. However, in such cases, the potential and current measurements, if made, will have no very significant meaning.

In any type of survey it must be realized that there are numerous points throughout the cable duct where the cable sheath is subject to small local potentials due to such causes as differential aeration, concentration cells, and so forth. With the cable in place these potentials are inaccessible for measurement, and, if the cable be removed, the original conditions no longer exist. The potential of these local cells are usually small but in aggravated cases may be in the order of 0.1 to 0.2 volt. In general, it may be assumed that these small local potentials exist, to a greater or less extent, in all ducts containing cable. Their effectiveness in causing cable-sheath corrosion will depend upon the resistance of the environment in immediate contact with the cable sheath and the polarizing effects due to the flow of current. This emphasizes the importance of duct resistance and its influence on cable-sheath corrosion.

Analysis of Duct-Survey Data

An accurate evaluation of an electrolysis condition can be obtained only through the proper analysis and interpretation of the test data. Readings of potential and current have no particular significance, unless they can be translated into terms of corrosion on the cable or piping system concerned. The desired interpretation of test data can be obtained best through the systematic investigation of the conditions incidental to corrosion cases and through studying the accummulated data in accordance with appropriate statistical methods.

Electrolysis test data serve two general purposes:

1. For individual cases, they serve to identify the cause and furnish the information required for the application of suitable remedial measures to the particular case concerned.

2. When properly classified and analyzed, together with other similar data taken systematically over the system, they constitute the basis for statistical studies of the conditions existing on the system as a whole.

For these reasons, the systematic taking and recording of data by trained observers in accordance with a well-developed plan is of first importance in making electrolysis surveys and in planning for over-all improvements on the system.

The foregoing general principles have been applied to the analysis of the duct-survey data obtained over a period of years with a view to showing the relationship between the data and actual cable-sheath corrosion. The results of the duct-resistance surveys made uniformly over the system are given in Figure 2. Curve *A* shows the duct resistance plotted on a cumulative percentage basis for approximately 9,500 duct-resistance tests made at random but well-distributed points on the system. This curve shows, for example, that in 65 per cent of the tests the duct resistance was above 1,000 ohms and less than 1,000 ohms in 35 per cent of the tests, curve *B* of the figure is a similar percentage curve of duct-resistance obtained in connection with approximately 200 cable failures. From this curve it will be noted that only five per cent of the corrosion failures occurred in ducts having resistance of 1,000 ohms or more. Further it will be noted that 70 per cent of the corrosion failures occurred in ducts in which the resistance was 250 ohms or less, whereas in curve *A* only six per cent of the total tests was under 250 ohms. These results indicate that the greater portion of the corrosion is occurring on a relatively small part of the system, that is, 70 per cent of the corrosion is occurring in approximately six per cent of the ducts. In general the curves show the importance of duct resistance as a factor in rating ducts with respect to corrosion. On the basis of the data, ducts in which resistances of 250 ohms or less are measured are rated unfavorably from the standpoint of corrosion.

To relate test data with actual corrosion and to establish a basis for the interpretation of the duct survey, studies were made of the potential, the current, and the resistance data obtained in the investigation of approximately 100 corrosion failures for which complete and consistent data were obtained.

Figure 3 shows the distribution of cable life as related to the average current discharged from the test electrode to the duct wall at or near the point of failure. For this purpose the cable life, from the date of installation to the date of failure, was grouped into yearly periods, that is, all failures falling within *N* years minus five months and *N* years plus six months were grouped under *N* years. The vertical columns in the figure show the averages of the current measured for the failures in each of the yearly groups. The standard deviation from the mean value of current was computed and shown by the vertical line associated with each of the columns. The magnitude of the deviations and other elements in the data show that the variations for any period are more than can be attributed to chance and prohibit a correlation between corrosion and the average current as measured. Furthermore, the lack of correlation is also evident from the fact that the contact area of electrode varies considerably under different duct conditions, thus introducing the question of duct resistance.

In order to incorporate duct resistance as a factor in the analysis, the data were grouped, for convenience, into two-year periods and the current plotted with respect to duct resistance on semilog paper as shown in Figures 4*a* to 4*e*. Straight lines were drawn to show the best averages between current and duct resistance in each of the groups. From these figures curves were constructed showing the relations between cable life and current for four values of duct resistance as shown by the curves in Figure 5. In comparing Figure 5 with Figure 3 it will be seen that the deviations from the average in Figure 3 readily can be accounted for by variations in the duct resistance. Although there is some variation in the resistivity of the duct contents and the duct wall, it is believed that the duct resistance depends primarily on the area of contact. Consequently, for a given total discharge per foot of cable, the current per unit area is relatively less in the low resistance ducts, that is, one milliampere measured in a 50-ohm duct represents a much lower current density than the same current measured in a 400-ohm duct.

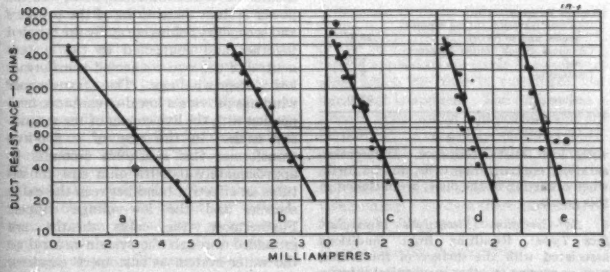

Figure 4. Electrode current versus duct resistance for cable in five age groups

The data are those used in Figure 3, but recognition is given to duct resistance

a—Six years
b—Eight years
c—Nine and ten years
d—11 and 12 years
e—13 and 14 years

The relationship shown in Figure 5 between cable life, discharge current and duct resistance has been confirmed in numerous surveys. For example, in a recent case involving a 13.2-kv oil-filled tie feeder, the survey showed a duct resistance of approximately 500 ohms and a discharge of 0.9 milliampere at a point where corrosion had penetrated the cable sheath. By interpolation from Figure 5, the probable life of the cable was estimated at four to five years. Corrosion also had penetrated the sheath at a second point in the same duct where the duct resistance amounted to 200 ohms, the current was 2.4 milliamperes, and the estimated cable life was slightly less than four years. The feeder had been in service four years and two months at the time of failure. The corrosion in this case was caused by soil potentials resulting from the cinder-filled soil adjacent to the duct bank. Typical duct surveys are shown in Figure 6.

Classification of Cable-Sheath Corrosion

A consideration of the foregoing emphasizes the necessity for a procedure to identify the various corrosion factors concerned and to permit their classification or grouping with respect to the various types of attack. For this purpose the corrosion on the underground cables of the Consolidated Edison system is divided for convenience into three general categories:

1. Direct chemical attack.
2. Stray-current electrolysis.
3. Electrolytic-cell (galvanic) corrosion.

In the case of cables occupying a duct system, it is important to distinguish between corrosion occurring in the ducts and corrosion occurring in manholes, pull boxes, service boxes, and so forth. Duct corrosion results from certain factors in the soil or duct over which the operating company has only partial control, whereas manhole corrosion usually occurs under the arcproofing or at bond wires, splice-filling nipples, and other dissimilar metal attachments where installation methods do not provide adequate protection. The importance of treating manhole and duct corrosion separately has been recognized on the Consolidated Edison system and the methods for protecting manhole cables and splices have been modified to insure adequate protection in the future.

When the classification of corrosion is considered with a view to the identification of the various factors under field conditions and the practical application of protective measures, the following grouping of causes has been found convenient and workable.

1. Stray-Current Anodic Corrosion. The corrosion caused by the electrolytic action of direct current picked up from foreign sources and discharged into an environment which acts as an electrolyte. The action occurs at the anode or point from which the current is discharged.

2. Stray-Current Cathodic Corrosion. This type of corrosion is caused by the secondary reactions of the cathodic products of electrolysis. The action occurs when direct current flows to the cable sheath from an environment containing dissolved salts, which are corrosive to lead.

3. A-C Electrolysis. The corrosion caused by alternating currents flowing between underground structures and earth is negligible at the usual current densities encountered in practice.

4. Soil Corrosion (Electrolytic-Environment Type). Corrosion resulting from electrolytic-cell potentials originating in the environment due principally to differences in the characteristics of the soil external to the duct bank.

5. Duct Corrosion (Electrolytic-Environment Type). Corrosion due to conditions existing in the duct and usually associated with low duct resistance. Differential-aeration, concentration cells, and so forth, when occurring in the duct, are included in this group.

Table I

	Per Cent (Approximate)
Duct Failures	
Stray current (anodic)	7.0
Stray current (cathodic)	1.0
A-c electrolysis	0.0
Soil corrosion	6.0
Duct corrosion	24.0
Self-corrosion (sheath scoring)	10.0
Galvanic corrosion (iron-pipe ducts)	7.0
Chemical corrosion	4.0
Unclassified	6.0
Subtotal	65.0
Manhole Failures	
Galvanic corrosion (filling nipples, bonds, and so forth)	23.0
Chemical attack (under arcproofing)	9.0
Unclassified	3.0
Subtotal	35.0

6. Self-Corrosion (Electrolytic Metal-Surface Type). Resulting from conditions associated with the surface of the metal, such as scoring or other mechanical injuries which may set up local galvanic cells on the surface of the metal.

7. Galvanic Corrosion (Dissimilar Metals). Resulting from the contact of dissimilar metals in the presence of an electrolyte in manholes and ducts.

8. Chemical Corrosion. Corrosion which results from the direct chemical action of certain acids and alkalies on lead-cable sheath in manholes and ducts.

The application of the foregoing classification to the corrosion failures for a four-year period on the high-voltage cables of the Consolidated Edison system gives, approximately, the percentages listed in Table I.

The corrosion rate for 1943, per 100 miles of occupied duct, amounted to approximately 0.82 for the high-voltage cable system. Furthermore, approximately 30 per cent of the corrosion failures occurred in certain corrosive areas representing less than 1.0 per cent of the duct system. Manhole corrosion failures are less restricted to areas and are distributed more widely than those occurring in ducts. The corrosion rate has been reduced from 1.13 in 1940 to the present rate by the application of protective measures in the areas identified as corrosive.

Mitigation of Cable-Sheath Corrosion

Electrolysis Drainage

Electrolysis drainage is used extensively for the mitigation of stray-current electrolysis on the cable system. Drainage consists essentially in providing a connection between the cable sheath and the negative bus or negative returns of the railway system involved. The object is to provide a metallic return for stray railway currents picked up by the cable system and thus to lower the potential of the sheath below that of the surrounding earth in the normally positive areas. Where the cables thus are maintained at a negative potential they also are protected by cathodic action against the galvanic types of corrosion.

The drainage of a power system presents more difficult problems than are encountered in the drainage of communication cables or railway cables which are not included in a distribution system. In the power system the sheaths of the primary and secondary cables normally are bonded together and connected to the system neutral of the wye-connected transformer low-voltage windings. These transformer windings provide a low d-c resistance connection with the live copper of the secondary cable. In the case of a 500-kva transformer this resistance amounts to approximately 0.00013 ohm and constitutes an effective bond between the cable sheaths and the low-voltage copper. Furthermore, the cable sheaths are grounded through the system neutral to the water system at customers' services. Consequently, when an attempt is made to drain the power system, the drainage not only applies to the cable sheaths, but also includes the system neutral, the copper in the low-voltage cables, and the water system. This very greatly reduces the effectiveness of drainage, and in the average situation it is estimated that only 30 to 40 per cent of the drainage current is effective in reducing the potential of the cable sheaths.

Where the power-system cables closely parallel communication cables or a railway cable system, there may be a considerable difference of potential between the cable systems resulting from the difference in the effectiveness of drainage

on the respective systems. This constitutes an important problem in reducing the effects of stray-current electrolysis on the power system. Where practical, control drainage is used, that is, resistors are connected in the drainage cables and adjusted to limit the current to that required to maintain the cable sheaths concerned slightly negative with respect to the duct wall. In some cases the power cables are bonded to the communication or railway cables to reduce potential differences between the systems.

Cathodic Protection

In certain instances, where applicable, the cathodic scheme of protection is used. There are several of these installations in operation on the power cable system in New York City. The scheme is used principally, where the electrolytic-cell type of electrolysis is the influencing factor.

Cathodic protection consists essentially in placing earth electrodes properly arranged with respect to the cable ducts concerned and in applying a positive potential for the purpose of raising the duct or earth potential sufficiently to render the cable sheath negative with respect to the earth. In this arrangement, current flowing through the earth to the cable sheath tends to neutralize any positive sheath potentials likely to cause corrosion. Current at the required potential is supplied by motor generators or suitable rectifiers. The principles underlying cathodic protection have been described in several papers on the subject.[11,13,15]

In some installations of cathodic protection on the cable system, the anode consists of scrap cable installed in a vacant duct with its sheath connected through a rectifier to the cables under protection. Car rails buried adjacent to the duct bank have proved satisfactory in other installations where the current requirements are small. In cases where considerable current is required, the car rail should be imbedded in coke breeze, or specially designed carbon electrodes should be used. In one of our installations plain car rail has been in service for approximately six years, discharging an average of ten milliamperes per foot of rail.

The cathodic scheme of protection has met with considerable success on long pipe lines and cables where other structures are not seriously involved, and where there is sufficient right of way for the proper installation of the earth electrodes. Under the congested conditions found in New York City, the cathode method has but limited application. Where used, precautions must be taken to avoid discharging current to other structures which are not included in the protective scheme. Moreover, the current discharged from individual short electrodes or from sections of a long electrode laid parallel to the cables will vary between wide limits from point to point, depending on the soil conditions. There is danger in supplying too much current in some sections in order to obtain protection in others. In such cases there is grave danger of cathodic corrosion in the sections receiving an excessive amount of current. To avoid the possibility of cathodic reaction, the current should be limited to only that required to give protection, and its uniformity over the duct section should be checked by a duct survey.

Protective Coverings

Protective coverings are used on the cable sheaths in certain areas, where corrosion is caused by local soil and duct conditions and where drainage or other electrical methods for protection are impractical. The protective covering which has been most generally used on the Consolidated Edison system consists of coating the cable sheath with an asphalt compound and applying two layers of canvas tape saturated with the compound. This covering has afforded adequate protection for ten years or more under the most severe corrosive conditions existing on the system. However, considerable difficulty has been experienced in pulling this type of cable into or out of the cable ducts, because of the increased over-all diameter of the cable and the tendency of the compound to cement to the duct walls. In some cases where an attempt was made to remove the cable, it was found that the disintegrated fabric clogged the duct so as to make removal of the cable impossible. In such cases the ducts have to be abandoned.

Because of these difficulties, a special rubber-faced tape has been used in some of the recent installations. The rubber tape is applied to the cable in two layers after which the tape is vulcanized and mica dust is applied. The surface has a smooth finish which is of considerable aid in pulling. A quantity of the rubber-covered cable was installed, on an experimental basis, in 1940 to determine its durability and characteristics as a protective coating. To date there have been no failures in this type of coating.

Cable-Grease Protection

A special cable grease is being used extensively on the cable system for protection in areas subject to the environmental types of corrosion. This type of protection has been used on the power cables in New York City for the past four years. Another company has had ten to 15 years of experience with grease-coated cable. The results reported to date have been generally satisfactory.

The grease compound used is a heavy tacky petroleum grease very similar to axle grease. A little light oil is added by the manufacturer to make the grease workable. The grease is applied to the cable sheath by hand as it is pulled into the duct, care being taken to have the grease rubbed on all parts of the cable. The quantity applied amounts to approximately 25 pounds per 100 feet on cable having an outside diameter of three inches and proportionately less for smaller cable. In the use of grease for cable-sheath protection, it is important that the cable be installed in clean ducts. Any sand or mud in the duct will mix with the grease and leave a flaky coating without protective value.

Cleaning and Flushing Cable Ducts

In cases where the cable sheaths are subject to chemical corrosion, or in ducts in which alkaline or acid conditions exist, very beneficial results have been obtained by flushing the duct with hydrant water before installing the cable. Several corrosive conditions have been cleared up by this process. In one case, where ducts enter a substation through a massive concrete envelope, the ducts were flushed every three months for approximately one

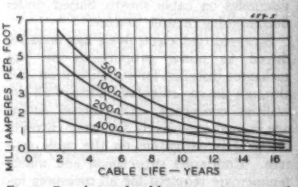

Figure 5. Age of cable versus current and duct resistance

Curves derived from the current–resistance data given in Figure 4

year before the recurrence of an alkaline condition finally was stopped.

The Use of Zinc for Cathodic Protection

Zinc electrodes are used in several system transformer manholes to provide cathodic protection to the transformer tanks. The electrodes, consisting of zinc bars 36 inches long and $^1/_8$ inch x 4 inches cross section, are placed on the walls of the manholes, bonded together and connected to the transformer tanks.

The zinc installations in question have not been in service for sufficient time to determine their effectiveness. The potential between the electrodes and the steel tank amounts to approximately 0.45 volt. The zinc is anodic and there is a definite flow of current from the electrodes to the tanks, which are painted so that this current reaches the metal through the pores and small defects in the paint coating. The current amounts to approximately 0.4 ampere for each transformer tank.

In a recent paper on the use of zinc for cathodic protection Wahlquist[14] calls attention to the advantages of this type of protection. He also points out that

zinc may not be applicable for use in locations where high resistivity limits the current output. Attention also is called to the formation of high-resistance films on the surface of the zinc and the use of chemical treatment for the reduction of these films.

Summary and Conclusion

The corrosion of metal underground is, to a large extent, the product of electrochemical processes. Electrolytic corrosion may result from stray current or from electrolytic cells associated with the metal or with its environment. Electrolytic corrosion may result from dissimilar metals in contact, or more usually from concentration cells set up in the environment by such factors as differential aeration or dissimilarity in the soils in contact with the metal.

Chemical corrosion is experienced most frequently under green concrete, in wooden ducts, and in service boxes or manholes on cable sheath buried under decomposing organic matter.

Stray-current electrolysis has been reduced to minor proportions by the measures installed for its mitigation and through the co-ordinated efforts of all the utilities concerned. Electrolysis drainage is used extensively for stray-current-electrolysis mitigation on the cable system. Continued supervision and maintenance are required for all measures installed for stray-current-electrolysis protection.

Corrosion from environmental conditions has increased in certain sections where the operation of trolley lines has been discontinued and where the cathodic protection afforded by the rails has been removed. The environment types of corrosion occur most frequently in soils of a heterogeneous nature and under conditions where the resistivity of the environment in contact with the cable is relatively low. Protection against environmental corrosion is obtained through the use of protective coatings or through the application of cathodic protection.

Electrolysis surveys are conducted on schedules arranged to give the required supervision and to detect, insofar as possible, new situations that may arise. The manhole tests usually made in connection with stray-current electrolysis do not give adequate information on the environmental types of corrosion. This has necessitated the development of a duct survey which will yield information on the conditions in the duct and furnish data by which the severity of corrosion conditions can be estimated.

A large percentage of the corrosion failures on the cable system occur in a few more or less well-defined areas comprising a small percentage of the total

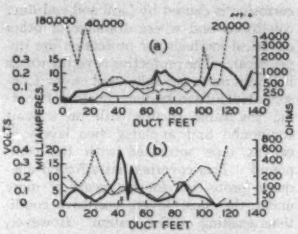

Figure 6. Typical duct surveys showing corrosion failures at points of low duct resistance

——— Milliamperes
——— Sheath potential
--------- Duct resistance
×—Cable failure

system. The failure rate has been reduced appreciably in the past five years.

The further mitigation of existing electrolysis conditions can be accomplished best by the application of corrective measures in the areas subject to environmental corrosion. In such areas the plans for new work should provide for the best possible duct construction and adequate manhole and duct drainage. In existing installations and in situations where it is impractical to control the environment, provisions should be made for the application of cathodic protection or the use of protective coatings.

Future development and research in electrolysis mitigation should include, as major projects, field studies of environmental conditions and the further development of existing and new types of protective coatings. Further study also should be given to the application of cathodic protection to both cable and piping systems in congested areas.

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Anode-Circuit-Breaker Design and Performance Criteria

E. W. BOEHNE
FELLOW AIEE

W. A. ATWOOD
NONMEMBER AIEE

THE rapidly expanding use of mercury-arc rectifiers, both as to total installed capacity and the relatively large number of units operating in parallel, emphasizes the importance of suitable switchgear to provide over-all satisfactory rectifier operation. The necessity for such switchgear, particularly for a high-speed air circuit breaker in the rectifier anode circuit, has been outlined in previous papers before the Institute.[1,2] During the past several years, considerable progress has been made in the reduction of arc-backs in power rectifiers. Anode circuit breakers, although subject to less frequent duty as a result of this progress, are required to operate at higher voltages and interrupt greater arc-back currents as indicated by recorded rates of rise of current in excess of 11,000,000 amperes per second. At this rate of rise in a large 650-volt (d-c) rectifier installation, the anode-breaker interrupting duty is equivalent to that of the first phase to clear a 130,000-kva fault in a three-phase 1,400-volt a-c system.

These power-duty requirements in the unique single-phase a-c-d-c circuit of the rectifier under arc-back dictate a further careful re-examination of the circuital requirements of the anode breaker which may assist in obtaining design and performance criteria. Such a study has been made and is presented herein, together with the performance of the General Electric Company's six-pole 1,600-ampere 750-volt type-*AG*-2 air circuit breaker under such requirements.

Summary

The arc voltage E_B developed by the anode-breaker, together with its early introduction into the circuit following current reversal, constitute the most essential performance criteria. It is shown that a current zero, the first prerequisite for interruption, can be created in the arc-back circuit only by developing a counter current (i_B) which neutralizes the arc-back current (I). This helpful concept is developed in a rigorous quantitative manner. The electromotive force for this counter current is the arc drop of the anode breaker (E_B).

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E. W. BOEHNE and W. A. ATWOOD are both with the General Electric Company, Philadelphia, Pa.

Contrary to general belief, the arc energy (k) developed by the anode breaker does not necessarily decrease as the arc voltage is introduced earlier in the circuit For each arc-voltage characteristic there exists a particular time of introduction, (θ_e), which gives maximum arc energy. Neither can the point of minimum energy be accepted as the desirable objective due to the relatively high initial recovery voltage (E_1) associated with this point. Optimum anode-circuit-breaker performance, in circuits having high rates of current rise, requires establishing the final current zero during the inverse-voltage period (E_1 negative) together with arc energies (k) which avoid the peak of the energy characteristic.

The modification of these results as affected by the ratio of the reactive ohms (ωL) to the resistance ohms (R) of the circuit is discussed on a quantitative basis. Quantitative variations in the various parameters are presented to study their effect. Certain unique characteristics of anode breakers are explained. An example of an anode-circuit-breaker malperformance, observed when testing a developmental breaker at elevated voltages, is presented with corrective measures indicated.

The entire study is carried out on a clearly defined per unit basis which permits the numerical values on all the graphs to be applied to any voltage system at 25, 50, or 60 cycles. All arc energies (k) are given on a 60-cycle basis in watt hours per megavolt-ampere, the latter being the product of the kilovolts of the effective alternating voltage and the corresponding symmetrical zero-power-factor kiloamperes produced in the inductive ohms of the equivalent circuit.

The embodiment of these principles in the high-speed *AG*-2 air circuit breaker is demonstrated with numerous field oscillograms. The new design features of this breaker are described.

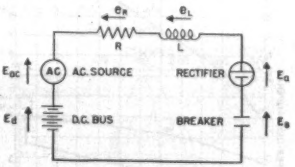


Figure 1 (above). Equivalent arc-back circuit of rectifier which is useful in the study of the performance of anode breakers

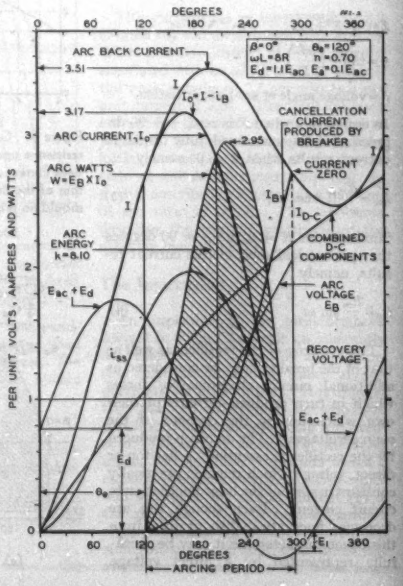


Figure 2. Sample calculation of the circuit of Figure 1 under practical condition of anode-breaker performance

The arc voltage of the breaker (E_B) produces the current (i_B) which neutralizes the arc-back current I, thus producing a current zero. The effect of rectifier arc drop has already been considered in the computation of I (see equation 6). The shaded area is the arc energy k released by the anode breaker

The Circuit

The actual circuit of the arc-back current in a rectifier[1,3] is of an inherently complex nature which fortunately has

been reduced[3] to the simple approximate and practical equivalent circuit shown in Figure 1. Here are found the well-known parameters of inductance (L) and resistance (R) both of which may be considered linear. Under arc-back, the current (I) is supplied by two separate sources of voltage, namely, an a-c and a d-c source designated respectively as E_{ac} and E_d. The analysis of this circuit is enhanced by considering each of the several voltages to act one at a time and to add the resulting currents to obtain the final result.

The Currents

The current produced by the direct voltage (E_d) acting alone is

$$I_d = \frac{E_d}{R}\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\} \qquad (1)$$

The current produced by the alternating voltage acting alone is given by the general expression for the short-circuit current in the R, L circuit. Since the contribution of the direct voltage given by equation 1 is already defined in its simplest terms, it becomes profitable to express the d-c component of the alternating current in a similar form, giving for the total a-c contribution

$$I_{ac} = \frac{E_m}{Z}[\sin(\gamma-\beta)+\sin(\omega t+\beta-\gamma)] - \frac{E_m}{Z}\sin(\gamma-\beta)\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\} \qquad (2)$$

where

$$Z=\sqrt{R^2+\omega L^2}; \qquad E_m=\sqrt{2}E_{ac}$$

$$\gamma=\tan^{-1}\left(\frac{\omega L}{R}\right)$$

β = voltage angle of arc-back initiation

In equation 2 when R is zero, $\gamma = 90$ degrees, and the undamped, fully displaced current results when $\beta = 0$, namely

$$I_{ac} = \frac{E_m}{\omega L}[1-\cos\omega t] \qquad (3)$$

Similarly, for $R = 0$ and $\beta = 90$ degrees the symmetrical short-circuit current results, namely

$$i_{ac} = \frac{E_m}{\omega L}\sin\omega t \qquad (4)$$

The arc drop of the rectifier, as well as that of the breaker, may be considered as additional circuit electromotive forces which in turn produce currents of their own which oppose the currents of the source voltages.[5] The arc drop produced by the rectifier is essentially a flat-top or direct voltage which remains practically constant in spite of the large fluctuation in circuit current. Even though this arc drop may fluctuate slightly or differ from this exact characteristic it may be faithfully represented by a direct voltage ($-E_a$) of an average constant magnitude. On this basis, the rectifier drop may be considered to produce its own current, namely

$$i_a = -\frac{E_a}{R}\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\} \qquad (5)$$

The total arc-back current (I), including the effect of rectifier drop ($-E_a$), may now be written as the sum of equations 1, 2, and 5

$$I=\left[\left(\frac{E_d-E_a}{R}\right)-\frac{E_m}{Z}\sin(\gamma-\beta)\right]\times\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\}+\frac{E_m}{Z}[\sin(\gamma-\beta)+\sin(\omega t+\beta-\gamma)] \qquad (6)$$

or $I = I_{DC} + I_{SS}$ (see Figure 2)

This grouping of all the transient components in one term (I_{DC}) simplifies the quantitative and graphical presentations and affords a clearer visualization of the effect of the various factors involved.

The majority of arc-backs initiate in the inverse period and create arc-backs at the end of the conducting period with the failure, for one reason or another, of rectification. The instantaneous value of the alternating voltage at the time of current reversal determines the value of β. It is a function of the angle of overlap of the rectifier which, in turn, is dependent upon the rectifier loading. For very light loading, including no load, the angle β may be as low as -30 degrees, or 30 degrees prior to a normal alternating-voltage zero. This condition would give the maximum arc-back currents. As the loading is increased, however, the angle of overlap is increased and the point of current reversal occurs close to a normal alternating-voltage zero or when β is zero. Since arc-backs are more frequent under load, it will be found practical to consider values of β close to zero. A simplification in the final arc-back current of equation 6 of practical significance

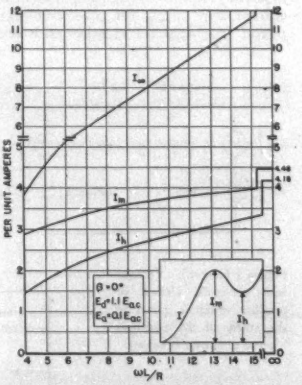
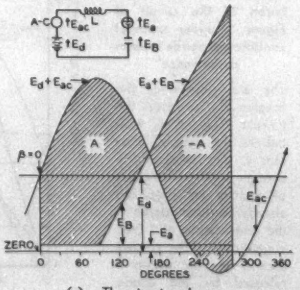
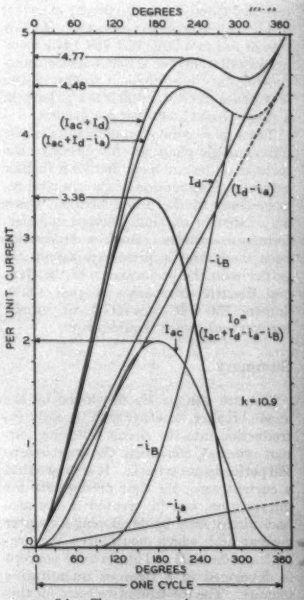


Figure 3. Curves showing the effect of circuit resistance upon the relative magnitude of arc-back current at the initial peak and at the bottom of the first dip, and the ultimate current should no protective equipment be employed

Rectifier drop is included



(a). The circuit voltages



(b). The corresponding currents

Figure 4. The voltages and the corresponding currents which would flow in the circuit of Figure 1 when resistance is zero

Each current is proportional to the area under the corresponding voltage, the net current I_0 being proportional at all times to the net shaded area as indicated in Figure 4a

results when the initiating angle β is made slightly negative so that $(\gamma-\beta)=90$ degrees. This results in a value of $\beta=-14$ degrees for a circuit whose ratio of $\omega L/R$ is as low as 4; -7.1 degrees for a $\omega L/R$ of 8; and for a ratio of $\omega L/R$ of 15, the value of β to satisfy this condition is only -3.8 degrees. These values fall between the practical limits of arc-back initiation of -30 degrees and 0 degrees. When $(\gamma-\beta)$ is made 90 degrees in equation 6, and the close approximation of ωL to Z is absorbed, there results

$$I=\left[\left(\frac{E_d-E_a}{R}\right)-\frac{E_m}{\omega L}\right]\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\}+\frac{E_m}{\omega L}[1-\cos\omega t] \quad (7)$$

This practical division places all the variables in the transient term and affords easy determination of the total current.

Quantitative Values and the Per Unit System

The numerical work in this paper is presented on a per unit basis and therefore is applicable to any system regardless of voltage, kilowatt capacity, or frequency.

Per unit voltage is $E_m=\sqrt{2}E_{ac}$

Per unit current is $I_m=E_m/\omega L$

Hence, ωL is unity on the per unit system

Per unit watts, $W=E_m\cdot I_m$

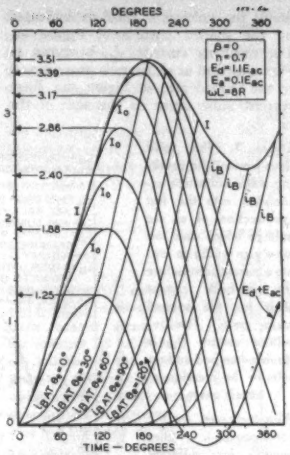
Per unit arc energy (k) is expressed as the watt hours per megavolt-ampere where the base megavolt-amperes is $0.5\times10^{-6}\,E_m\cdot I_m$. All values of k are expressed on a 60-cycle basis. For 25-cycle systems all values of k should be multiplied by 2.4 and for 50-cycle systems the value of k should be multiplied by 1.20 to obtain true values.

The ratio of the effective direct voltage (E_d) to alternating voltage (E_{ac}) in the rectifier circuit under arc-back may vary from 0.90 to 1.17, depending upon the number of rectifiers on the bus[3] and to a smaller extent upon the regulation of the a-c system. The value of 1.17 assumes an infinite d-c and a-c bus and is the upper limit. This condition is approached in large electrochemical installations where a large a-c source supplies the rectifier transformers. A value of 1.10 is chosen for this ratio for the numerical work in this paper. It is fairly indicative of large existing circuits in the electrochemical industry. Thus

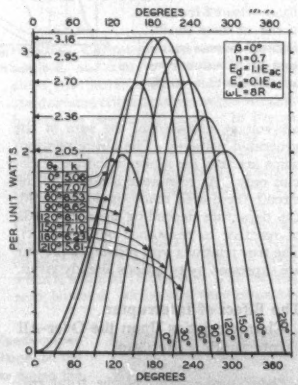
$$E_d=1.10E_{ac} \quad (8)$$

Likewise the arc drop of the rectifier (E_a) depends upon the type of rectifier employed. Expressing this direct voltage in per unit of the rms value of the alternating voltage facilitates the numerical presentations on a per unit basis. A rectifier drop under arc-back of ten per cent of the alternating voltage is chosen as being indicative of the higher voltage systems. This percentage is slightly pessimistic and, if used, will be more pessimistic for the lower voltage systems. The equations and method of attack permit the use of any value of rectifier drop. For the numerical cases presented in this paper

$$E_a=0.1E_{ac} \quad (9)$$



(a). The breaker generated current (i_B) produced by a linearly rising arc voltage, E_B ($n=0.70$), is introduced at 30-degree intervals, the corresponding arc currents (I_o) being shown ($I_o=I-i_B$)



(b). The corresponding wattage curves of Figure 5a. ($W=E_B\cdot I_o$). The area under each curve is the arc energy and is tabulated on the figure and plotted in Figure 6

Figure 5. Arc currents and their corresponding wattages for various contact parting times from $\theta_e=0$ degrees to $\theta_e=210$ degrees. The composite results of these values are plotted in Figure 6

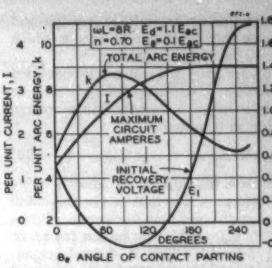


Figure 6. Master arc-interruption criteria resulting as the time of introduction (θ_e) of the arc voltage (E_B) is varied from zero to 210 degrees following the initiation of a high-capacity arc-back ($\beta=0$)

The composite data for these curves are presented in Figure 5

Adopting the ratios given in equations 8 and 9 as being indicative of the large rectifier installations, equation 7 becomes

$$I=\left[0.707\left(\frac{\omega L}{R}\right)-1\right]\left\{1-\epsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right\}+\{1-\cos\omega t\} \quad (10)$$

When the ratio $\omega L/R$ is taken as eight (used on many of the curves) the numerical equation for the arc-back current becomes

$$I=4.65\{1-\epsilon^{-0.125\,\omega t}\}+\{1-\cos\omega t\} \quad (11)$$

This current has an initial peak of 3.6 (Figure 10) and an ultimate peak of 6.65. When β is zero instead of -7.1 degrees, associated with an $\omega L/R$ of eight, the initial peak is reduced 2.5 per cent to a per unit current of 3.51. The total arc-back current for the case of $\beta=0$ is shown in Figure 2. The relative magnitude of the initial current peaks (I_m) and the magnitude at the initial current dip (I_h) for $\beta=0$ is described in Figure 3 as a function of the ratio of $\omega L/R$. The top curve describes the relative magnitude of the ultimate current peak, I_∞.

The Interrupter

An inspection of the total arc-back current in Figure 2 reveals an inherently d-c characteristic in that no natural current zeros are present to afford an opportunity for interruption. It is imperative that an interrupter be employed which is capable of producing a current zero. This is only possible by producing an arc voltage in the interrupter which is capable of causing a current to flow which will neutralize the circuit current (I) of the arc-back. This in turn demands a circuit breaker capable of developing sufficient arc drop and thus inherently avoids an oil breaker as the latter func-

tions on the low-arc-voltage principle and is hence only adaptable to circuits which afford a natural current zero.

The arc drop (E_B) of a self-contained air breaker of the magnetic type may be represented by a linearly rising voltage having an equation

$$-E_B = n \cdot E_m \cdot \omega t \qquad (12)$$

where n is the slope of the linearly rising arc voltage in per unit of the maximum slope of the per unit a-c source. When $n=1.0$, $E_B=E_m$ at one radian ($\omega t=1$ or 57.3 degrees). This is defined graphically in the lower left-hand corner of Figure 7.

The current produced by this linearly rising voltage in the L, R circuit is

$$i_B = \frac{nE_m}{R}\left[\omega t - \frac{\omega L}{R}\left(1-\varepsilon^{-\left(\frac{R}{\omega L}\right)\omega t}\right)\right] \qquad (13)$$

This current is not admitted to the circuit until the contacts of the breaker part θ_s degrees later and permit the rapidly expanding arc to develop the linearly rising arc voltage of equation 12. This current is shown in Figure 2, introduced by a breaker which parts its contacts in one third of a cycle ($\theta_s=120$ degrees or $\omega t=2\pi/3$) and which develops an arc voltage which rises linearly at a rate of 0.70 of the maximum slope of the a-c source ($n=0.70$). The actual net circuit current I_a is the difference between these two currents and is also plotted in Figure 2 as the oscillograph would record this current. It follows that the peak available current will be lowered and will occur earlier as the arc voltage of the interrupter is introduced earlier in the circuit.

A clearer visualization and working knowledge of these various relationships which avoid the apparent complexity of the equations which appear above is to consider the same circuit without resistance ($R=0$). In this case, which is a close approximation for large rectifiers, each of the several currents will be proportional at all times to the volt-time area under the respective voltages. This comes about in any pure inductive circuit since

$$i = \frac{\int e\,dt}{L}$$

which is merely another way of expressing the fact that

$$e = L\frac{di}{dt}$$

The currents in the pure inductive arc-back circuit [zero power factor, ($R=0$)] are shown in Figure 4b. Each in turn is proportional to the area under the corresponding voltage in Figure 4a. The net current is hence proportional to the net volt-time area acting on the inductance. It follows that from the initial current zero to the final current zero, the net area under the voltage is zero[5] as indicated by the shaded portion of Figure 4a. The resulting current, I_a, is shown in Figure 4b and at all times is proportional to the shaded area in Figure 4a. Peak current must occur as the sum of the arc-voltage drops equal the sum of the generated voltages. The above relationships are true for a purely inductive circuit only. As resistance is added to the circuit these area relations do not hold, the departure depending upon the ratio of reactive to resistance ohms ($\omega L/R$). The true relations with resistance present are expressed by equations already given.

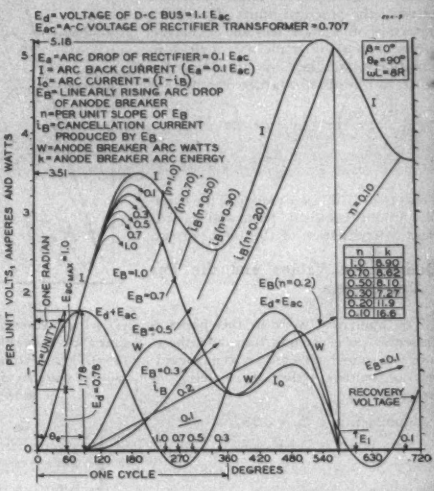


Figure 7. The solid lines portray the resulting malperformance associated with the fast introduction of an arc voltage which rises too slowly ($n=0.2$) to create a current zero before the arc-back current starts for the second major peak. The resulting current (I_a) is double-humped and results in the creation of excess energy

Also indicated are the corresponding phenomena for different arc-voltage slopes varying from n equal to 1.0 to 0.10. The corresponding breaker energies are tabulated on the figure. Figure 8 is a composite of these results. Figure 9 shows a typical case of the malperformance similar to $n=0.20$

The exact interrelation between items 2 and 3 above is complex and will vary depending upon the interrupter. Nevertheless, it becomes obvious that low arc energy followed by a current zero which occurs at a time when the instantaneous recovery voltage is low is a desirable combination for good interrupter performance. In Figure 2 is shown a complete sample calculation on a per unit basis which determines these factors for the following conditions:

1. $E_d = 1.10E_{ac}$
2. $E_a = 0.1E_{ac}$
3. $(E_d - E_a) = E_{ac}$
4. $\beta = 0$
5. $\theta_s = 120$ degrees
6. E_B = linearly rising
7. $n = 0.70$
8. $R = \omega L/8$
9. $\gamma = 82.9°$
10. $Z = 1.008\omega L$

The maximum per unit value of the initial current peak is 3.51 which is limited to 3.17 by the arc voltage. The arc-wattage curve (W) is the product of the arc voltage and the arc current. It is computed graphically. Its area is the arc energy (k) in watt hours per megavolt-ampere on the base previously defined. For example, in a 650 volt (d-c) rectifier installation (alternating voltage 590) having a ratio of ωL to R of eight, which initiates an arc-back as the alternating voltage passes through zero ($\beta=0$) and produces an initial rate of rise of current of 11,000,000 amperes per second to an initial crest of 90,000 amperes, the value of

The Effect of Interrupter Characteristics Upon the Over-All Interruption Problem

The determination, of the total arc-back circuit current, by superimposing the separate contributions, enables the effect of variations of any particular voltage to be studied easily. Of particular interest is the examination of the effect of various anode-breaker arc-voltage characteristics upon the total current as well as other important circuit-breaker interruption criteria.

The three primary considerations which have a direct bearing upon the successful interruption of the arc-back current are:

1. The creation of a current zero.
2. The instantaneous recovery voltage at current zero and the resulting recovery-voltage characteristic.
3. The total arc energy liberated just prior to current zero and its distribution.

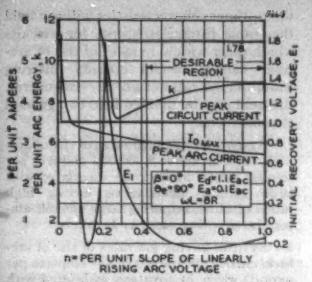


Figure 8 (left). Master arc-interruption criteria resulting as the slope (n) of the linearly rising arc voltage (E_a) is varied from 1.0 to 0.10

The individual cases are indicated in Figure 7. The arc-voltage initiating angle θ_e is constant at 90 degrees

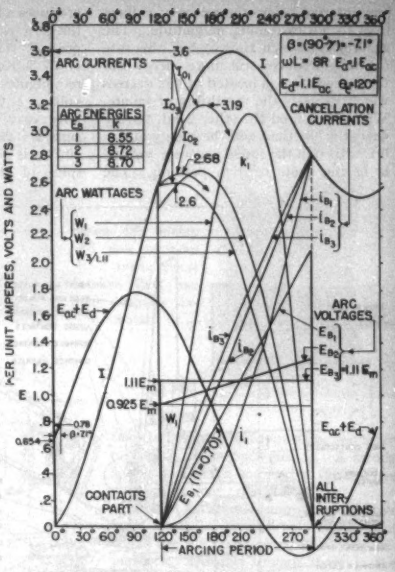


Figure 10. Arc currents and wattages resulting from three separate shapes of arc voltages, all of which are initiated at the same time ($\theta_e = 120$ degrees) and which produce current zeros simultaneously. Arc energies are tabulated on the figure

Note for this case the value of β is chosen as -7.1 degrees which permits l to be expressed by equation 7 of the text

the per unit current would be 90,000/3.51 = 25,600 amperes = I_{ac} maximum. The symmetrical alternating current would then be 18,100 and produced by an alternating voltage of 590 volts or a megavolt-ampere of 10.7 on a single-phase basis. Hence, the total arc energy having these values, developed as described by Figure 2, would be: 8.1 × 10.7 or 86.5 watt-hours. This is approximately the energy released by the anode breaker in clearing such arc-backs which take place following the conducting period. During such an interruption, the peak circuit current of 90,000 amperes would be limited to only 81,000 amperes, which occurs at 0.46 cycle, and current zero would take place during the inverse-voltage period as desired and indicated by Figure 2. An oscillogram closely approaching these conditions is shown in Figure 14.

Effect of Breaker Speed

It is of interest now to examine the corresponding results of Figure 2 when the arc voltage is initiated at various intervals, θ_e, following the current reversal. The results of this variation are presented in Figure 5. In Figure 5a are shown the breaker-generated currents (i_B) and the resulting current-limiting action as the angle θ_e is taken to zero in 30-degree-steps (the latter case would require instantaneous tripping of an anode breaker having no mechanical time). In Figure 5b are shown the corresponding arc-wattage curves together with their areas tabulated on a per unit energy basis on the figure. These characteristics are plotted in Figure 6 and show the interesting fact that, for the particular representative arc-voltage characteristic chosen, the arc energy reaches a crest when θ_e is about 75 degrees. The current zero, however, occurs at a very favorable point to assist the interruption, and the external circuit is benefited by additional current-limiting action. When the same arc voltage is admitted at 150 degrees, however, the energy is reduced to 82 per cent of the maximum value and current zero is still in a favorable region. The peak current on the other hand is 19 per cent in excess of the peak current at the maximum energy point.

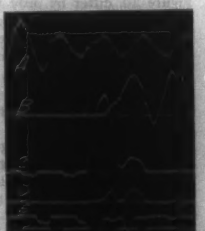


Figure 9. Oscillogram showing a malperformance which occurs should the developed arc voltage of the breaker rise too slowly to create a current zero during the dip in arc-back current following the initial peak

See Figure 7 ($n = 0.2$) for a graphical interpretation of this phenomenon. This record was obtained by testing a 650-volt developmental anode breaker at 1,030 volts

Curve *A*. Sixty-cycle timing wave

Curve *B*. Anode-breaker voltage (E_B) and recovery voltage ($E_{ac} + E_d$)

Curve *C*. Anode current of faulted pole as limited by anode breaker (I_a) (see Figure 7)

Curve *D*. Anode-breaker watts (W)

Curve *E*. Forward current of anode circuit of another pole on same wye

Curve *F*. Forward current of anode circuit of remaining pole on same wye

Curve *G*. Voltage across the MC-5 air circuit breaker used to short-circuit the rectifier to create the simulated arc-back current

Effect of Rate of Rise of Anode-Breaker Voltage

In a similar manner, it is of interest to vary the slope (n) of the linearly rising anode-breaker arc voltage (E_B), keeping a fixed value of its point of initiation (θ_e). Such a study is sketched in Figure 7 by indicating the performance for values of n of 1.0, 0.7, 0.5, 0.3, 0.2, and 0.1 and all for a value of θ_e of 90 degrees. The case of $n = 0.2$ is shown in detail to exhibit the phenomena resulting when the arc voltage is so low that its cancellation current (i_B) does not neutralize the arc-back current before the latter rises toward the second current peak. Note the double-peaked current I_a. Figure 9 exhibits an oscillogram of such an occurrence. This was obtained when a 650-volt developmental anode breaker was tested at 1,030 volts.

In spite of the large increase in arc energy associated with this case ($n = 0.2$) an opportunity to clear is presented by the fact that the ultimate current zero at 570 degrees occurs at a low value of recovery voltage (E_1) and is followed by a relatively

long interval before the recovery voltage rises to a threatening magnitude. The arc voltage which rises at half this rate ($n=0.1$) produces still more energy and the current zero is located at 692 degrees which suggests the possibility of failure. When $n=0.3$, on the other hand, the arc energy is less than half the energy at $n=0.1$, although the initial recovery voltage is in the same relative position. The

produces a linearly rising current (i_{n1}) in the R, L circuit. This current reaches a per unit value of n in one radian ($\omega t=1$ or 57.3 degrees) and hence crosses the rectangular portion of the trapezoidal voltage at that point. It is also particularly easy to consider. The peak arc currents are merely indicated in Figure 10. It is particularly significant that, in spite of the difference in arc-voltage

the optimum characteristics will not hold the same interrelationship for circuits which differ widely in rates of rise of arc-back current or for circuits differing widely in the ratio of $\omega L/R$. In general, the field may be divided into two general classifications:

1. Systems having high rates of rise of arc-back current (above 8,000,000 amperes per second) which in turn are associated with large rectifier installations having high ratios of $\omega L/R$, requiring large kilovolt-ampere interrupting capacity breakers.

2. Systems having low rates of rise of arc-back current (below 8,000,000 amperes per second) which in turn are associated with smaller rectifier installations having lower ratios of $\omega L/R$ and requiring breakers of smaller kilovolt-ampere interrupting capacity.

Two breaker characteristics are thus indicated. It is the purpose now to describe

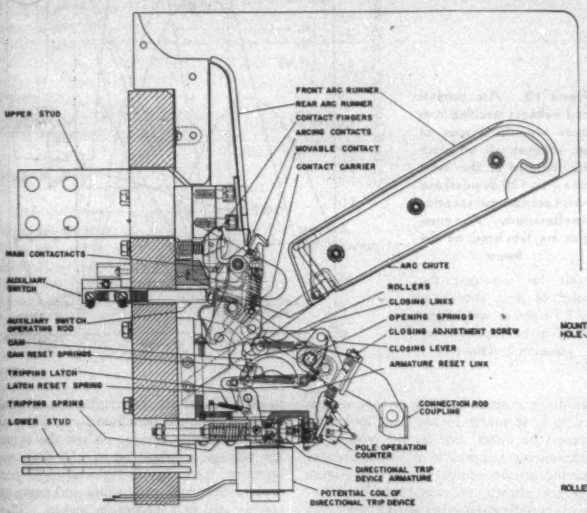


Figure 11a (above). Type AG-2 anode-circuit-breaker contacts, arc chute, directional trip mechanism, and auxiliary switch

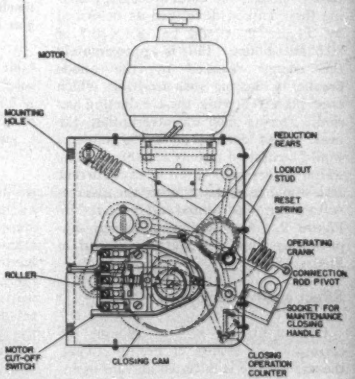


Figure 11b (right). Motor-operated closing mechanism for type AG-2 anode circuit breaker

master characteristics for this variation in n are presented in Figure 8. This study reveals that, for a given time of introduction of the arc voltage of the anode breaker, the energy characteristic increases as the slope of the linearly rising voltage is increased. The current zeros, however, are more desirably located in the inverse-voltage period for the higher values of n.

Effect of Arc-Voltage Shape

Although a linearly rising arc voltage of the anode breaker was chosen to demonstrate the various performance characteristics, the method is applicable to any type of arc-voltage wave shape. In Figure 10, for example, are shown three arc-voltage characteristics which start simultaneously and produce current zeros simultaneously in a circuit having a ratio of $\omega L/R$ of eight. The flat-top arc voltage is particularly easy to analyze since it produces a current (i_n) of the form $(1-\epsilon^{-(R/\omega L)\omega t})$ as shown. The special trapezoidal arc voltage (E_{n1} of Figure 10) having the equation

$$E_{n1}=n\left[1+\left(\frac{R}{\omega L}\right)\omega t\right]E_m \qquad (14)$$

shape, the arc energies (k), as shown in Figure 10, differ by only two per cent. Space does not permit the modulation of these other arc-voltage characteristics with respect to magnitude and point of initiation.

Conclusions From Analytical Study

It follows from the foregoing that the anode-circuit-breaker designer has the opportunity of selecting the most desirable combination of the three primary characteristics:

(*a*). Point of introduction of arc voltage.

(*b*). Arc-voltage shape.

(*c*). Arc-voltage magnitude which will best fulfill the requirements for satisfactory anode-breaker performance.

There are numerous combinations of these variables which will achieve comparable performance. It also can be shown that a breaker developed for the higher-duty requirements.

A High-Capacity Anode Circuit Breaker

The General Electric Company's six-pole 1,600-ampere 750-volt type *AG-2* air circuit breaker is quite similar in general appearance and much of the detail structure remains as it was in the breaker described in the Seaman-Morton paper[1] presented in November 1942.

To meet the increased interrupting capacity at the higher rates of rise of current, changes have been incorporated in the latest anode breaker to achieve improved operating characteristics, performance, and life. Advantage has been taken of the trends indicated by the analytical study presented in the early portions of this paper[2].

The most noticeable changes lie in the upper stud, contacts, and interrupter

unit construction (see Figure 11). Field tests with this open-chute construction have demonstrated that blowout coils contributed little to the over-all performance and as a result have been eliminated. Rapid arc motion following contact separation is enhanced by the hairpin loop in the current path to the arcing tips, the use of silver–molybdenum arcing tips, and steel arc runners. The back steel runner is mounted directly on the breaker upper stud and the stationary silver–molybdenum arcing tip is secured directly on the runner. The front runner is connected from its lower end to the lower stud of the breaker.

The arc chute has been somewhat increased in size and better insulation has been provided between the two arc runners in the chute by using Mycalex insulation and bushings to separate the front runner from the sides of the arc chute. Inside the arc chute there is practically no material to carbonize (see Figure 12). Only the steel runners, a small area of Mycalex, and the treated asbestos-board sides are exposed to the arc. The steel arc runners, because of the blowout effect established by the arc current which causes the arc to travel very rapidly along the runners, remain relatively cool and give up a minimum of metal to find its way into the arc stream. The minimizing of metal vapor in the arc stream works toward the establishment of an arc path of high resistance which is capable of creating and maintaining the arc-voltage characteristic required for optimum performance.

Curved ends on the arc runners are an aid in keeping metal vapor out of the arc stream because the point of arc contact on the runner does not hold to any one spot until interruption occurs. In a straight runner ending abruptly, an arc generally plays off one point until interruption, thereby raising the temperature of the runner to the melting point and feeding metal into the arc until the arc is broken. The arc-chute materials have been given standard treatments used on arc chutes of 15-kv air circuit breakers.[4] These treatments improve the arc-voltage characteristics of the chute and afford an increase in the dielectric strength of the open breaker.

The upper studs are redesigned so that the front portion carrying the back arc runner with its attached silver–molybdenum arcing tip may be removed as a unit to permit ready access to the primary contact fingers. The upper studs may have either vertical or horizontal bars extending through the panel to the rear for ease in making main connections. Each primary contact finger, of which there are three, has pivoted therein a spring guide through which a strong compression spring acts on the contact finger rather than seating the stiff spring directly on the finger, as was done formerly.

Figure 12a (left). One pole of AG-2 anode circuit breaker with new open-type arc chute with side plate removed. The curved steel runners permit rapid arc motion and keep metal vapor to a minimum

Figure 12b (right). End pole of type AG-2 anode circuit breaker. End and front barriers removed

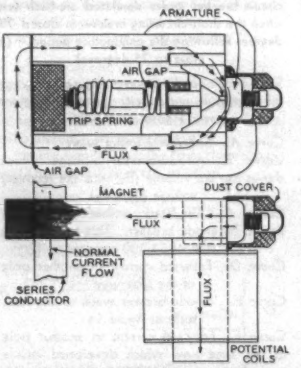


Figure 13. Directional-trip magnet structure showing dustproofing cover over armature

This permits the fingers to adjust themselves more readily in positions to give low contact drop. Primary contact fingers now may be removed for inspection, if necessary, or replaced from the front without removing the whole stud, thus leaving main connections undisturbed, an improvement over the original construction.

From the primary fingers, main current is carried through silver contacts to the bridge to the lower stud. Advantage is taken of the magnetic forces set up by the current being carried through the breaker to increase pressure at all contacts, but as further insurance against pitting at the lower contact, the bridge is connected by a flexible copper braid to the lower stud. The pivot in the bridge carrier which supports the bridge is also the pivot for a new arcing tip arm with a silver–molybdenum tip. This arcing tip is connected directly to the lower stud by an extension of the copper braid, previously mentioned, which connects the main bridge and lower stud. The arcing tip arm is adjustable for position, to secure proper operating sequence of main and arcing contacts. A strong spring biases the arcing tip toward the contact making position.

Certain additional improvements have been made in breaker-pole mechanism which are the result of excellent field experience. Notable among these is the addition of a dustproofing cover (Figure 13) which protects the armature and pole faces of the directional trip device.

Field Tests

When anode-circuit-breaker tests are made at the site of a rectifier installation, arc-back currents are created by short-circuiting the rectifier by a suitable short-circuiting breaker; namely, one free from arcing during the closing stroke. The drop created by such a breaker is small and cannot be considered as representing the arc drop in the rectifier during actual arc-back. As a result, the simulated arc-back current is increased and rises at a higher rate than the natural arc-back. But more important, the rectifier's interrupting capacity is not made available to divide the resulting recovery voltage with the anode breaker. In other words, the entire burden of interruption, under slightly more severe conditions, is placed squarely upon the anode breaker under test. The ability of the anode breaker consequently is tested under quite pessimistic conditions.

A typical test made at a large 650-volt (d-c) rectifier installation is shown in Figure 14. Curve *F* is the arc-back current of full magnitude which rises to 79,000 amperes at a rate of 11,400,000 amperes per second. The arc voltage is shown in curve *B* while the arc wattage is recorded in curve *E* which, measured, represents 82 watt-hours of energy. The crest current of the test circuit is 88,000 amperes. The per unit megavolt-ampere of the circuit as described in the early

Figure 14. Typical simulated arc-back test of the type AG-2 anode breaker on a large 650-volt rectifier installation

Curve *A*. Sixty-cycle timing wave
Curve *B*. Anode-breaker voltage which shows the arc voltage (E_B) and the recovery voltage ($E_{ac}+E_d$)
Curves C and *D*. Forward currents in the other anodes on the same wye
Curve *E*. Anode-breaker watts. The peak wattage of this curve is 80,000 kw. The area under this curve represents 82 watt-hours ($k=7.5$)
Curve *F*. Simulated arc-back current as limited by anode breaker. This current has a crest of 79,000 amperes in a circuit capable of 88,000 amperes at the initial peak
Curve *G*. Voltage across the *MC*-5 air circuit breaker used to short the rectifier to create the simulated arc-back current. Same scale as curve *B*.

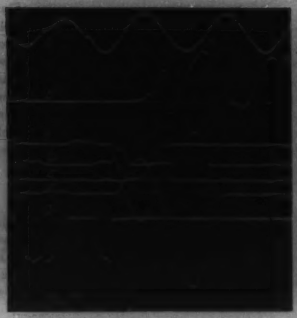


Figure 15. Performance of the *AG*-2 anode circuit breaker under simulated arc-back test when the short-circuiting breaker is closed 75 degrees following the conducting period. (β close to 75 degrees)

Same circuit conditions as in Figure 14 except different pole under test. Same calibrations as in Figures 14 and 16

Curve *A*. Sixty-cycle timing wave
Curve *B*. Anode-breaker voltage which shows the arc voltage (E_B) and the recovery voltage ($E_{ac}+E_d$)
Curve *C*. Simulated arc-back current as limited by anode breaker. This current has a crest of 51,700 amperes
Curve *D*. Forward current in another pole of the same wye
Curve *E*. Anode-breaker watts on the same scale as Figure 14
Curve *F*. Forward current in another pole of the same wye which developed into a sympathetic arc-back of 75,500-ampere peak which was cleared by the same pole tested in Figure 14. Effect of rectifier drop is present in this curve
Curve *G*. Voltage across the *MC*-5 air circuit breaker used to short-circuit the rectifier to create the simulated arc-back current. Same scale as curve *B*. The 75-degree delay is measured easily from this trace

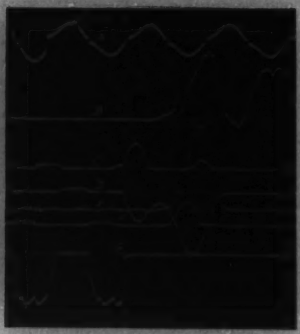


Figure 16. Simulated arc-back test in which the short-circuiting breaker closed 153 degrees following conduction resulting in a small initial current which tripped the breaker prior to the major rise of current

The rapid introduction of the arc voltage throttled this current to a 42,700-ampere peak. Arc energy, 67 watt-hours. All calibrations same as Figures 14 and 15

Curve *A*. Sixty-cycle timing wave
Curve *B*. Anode-breaker voltage which shows the arc voltage (E_B) and the recovery voltage ($E_{ac}+E_d$)
Curves C and *F*. Forward current in other poles on the same wye
Curve *D*. Simulated arc-back current in pole under test
Curve *E*. Anode-breaker watts
Curve *G*. Voltage across the *MC*-5 air circuit breaker used to short-circuit the rectifier to create the simulated arc-back current. Same scale as curve *B*

part of the paper is 10.9. The energy constant k for the test is 82/10.9 or 7.5 which may be compared with computed values of k shown on the figures.

A simulated arc-back is shown in Figure 15 where the value of β was determined by the random closing of the rectifier short-circuiting breaker. Here $\beta=75$ degrees. Interruption occurs promptly. Note the low arc wattage represented by trace *E*. Curve *F* exhibits a sympathetic arc-back on another phase of the same wye with maximum current of 75,500.

A case not uncommon during such a series of tests is shown in Figure 16. Here the arc-back is simulated by the random closing of the rectifier short-circuiting breaker at $\beta=153$ degrees, thus giving rise to a small current peak which is sufficient to trip the breaker. Prior to contact parting, however, the current has started for the first major peak where it is throttled by the action of the arc voltage to an early current zero. Peak current = 42,700. Arc energy = 67 watt-hours.

During such tests, simulated arc-backs are sometimes initiated later than 170 degrees thus causing only a small reverse current to flow which trips the breaker producing only the smallest spark. Such cases are recorded under actual arc-back conditions. Frequently on test, because of the absence of the rectifier in the circuit, such breaker trippings are followed by simulated arc-back currents after the intervening conducting period which are interrupted by the "pretripped" breaker under conditions representing a breaker having zero mechanical time. Such conditions are believed to be improbable during normal operation because of the healing provided by the rectifier during the intervening conducting period which prevents such "hyphenated" arc-backs.

Conclusions From Tests

A six-pole 750-volt anode breaker of simplified construction, embodying improved chutes of open construction, has demonstrated its ability to interrupt safely, repeated arc-back currents rising to 90,000 amperes at rates of rise in excess of 11,000,000 amperes per second. Peak currents in all cases have occurred in less than one-half cycle. After more than 100 tests at such currents, the contacts have been found in relatively good condition and the breaker required no imperative maintenance.

A contact of simple sturdy construction, employing no blowout coils, and assisted by a streamlined arc chute of high dielectric strength, enabled the development of a rapidly rising arc-voltage characteristic of high magnitude which is extremely stable. Properly introduced into the circuit by the action of a magnetic trip and a high-speed mechanism, this arc-voltage characteristic creates an over-all performance having optimum qualities with respect to established criteria of circuit interruption. A new and fundamental approach to the anode-breaker problem has been presented which enables the effect of controllable factors to be visualized and weighed with respect to over-all performance. In each

The Tapered Transmission Line

J. W. MILNOR
FELLOW AIEE

SEVERAL general mathematical solutions have been published dealing with the tapered transmission line as applied to communication service. These solutions [1–3] are in the form of a series or in Bessel functions, and are rather unwieldy for purposes of design.

Certain special plans of tapering, of which the exponential[4] is one, permit relatively simple solutions. It is the purpose of this paper to illustrate the applicability of such plans to practical wire-line tapering and to provide working formulas for design.

The tapering of loaded-wire lines and of lines for radio frequencies is useful, because of its transformer properties, in

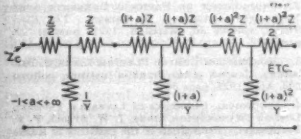


Figure 1. Lumped-tapered line showing impedance of each branch

coupling points in a circuit which have different impedances. In submarine cable telegraph practice tapering has been applied as an aid to duplex balancing to obtain two-way working.[7] For this purpose the central portion of the cable is heavily loaded, with the portion near each end nonloaded and the intermediate cable taper-loaded.

Exponential Tapering

The subject of tapering may be developed most simply by first presenting the solutions for the exponential plan. It is assumed here that the line parameters, for sinusoidal currents, follow:

$$\left.\begin{aligned}&\text{Line series impedance per unit of length} = Z_x = R_x + j\omega L_x = Z_0\epsilon^{ax}\\&\text{Line shunt admittance per unit of length} = Y_x = G_x + j\omega C_x = Y_0\epsilon^{-ax}\end{aligned}\right\} \quad (1)$$

in which x is the distance along the line, and a, Y_0, and Z_0 are constants; a may be positive or negative, corresponding to impedance which increases or decreases with distance from the origin.

At any point along the line, the voltage and the current bear the relation

$$-\frac{dE}{dx} = Z_0\epsilon^{ax}I \text{ and } -\frac{dI}{dx} = Y_0\epsilon^{-ax}E \quad (2)$$

The solution of these is

$$\left.\begin{aligned}E = \frac{b_1(\theta+a/2)\epsilon^{(-\theta+a/2)x}}{Y_0} + \frac{b_2(-\theta+a/2)\epsilon^{(\theta+a/2)x}}{Y_0}\\ I = b_1\epsilon^{(-\theta-a/2)x} + b_2\epsilon^{(\theta-a/2)x}\end{aligned}\right\} \quad (3)$$

in which b_1 and b_2 are constants, and $\theta = \sqrt{Y_0Z_0 + a^2/4}$

From these the next expressions follow directly: The characteristic impedance at any point x, looking away from the origin, is

$$Z_c = \frac{\theta + a/2}{Y_0}\epsilon^{ax} \quad (4)$$

In a line of length x terminated in its characteristic impedance, the ratios of received to sent voltages and currents are

$$\frac{E_r}{E_s} = \epsilon^{(-\theta+a/2)x} \text{ and } \frac{I_r}{I_s} = \epsilon^{(-\theta-a/2)x} \quad (5)$$

If the line be terminated by an impedance Z_r at the distance x, with sending from the origin, the line impedance looking from the origin is

$$Z_s = \frac{Z_0 + Z_r\epsilon^{-ax}(\theta\coth\theta x + a/2)}{\theta\coth\theta x - a/2 + Y_0Z_r\epsilon^{-ax}} \quad (6)$$

The ratio of received to sent voltages is

$$\frac{E_r}{E_s} = \frac{\theta Z_r\epsilon^{ax/2}}{\theta Z_r\cosh\theta x + (Z_0\epsilon^{ax} + aZ_r/2)\sinh\theta x} \quad (7)$$

Application to Wire-Line Tapering

Since the exponential tapering consists of a specified changing with distance of both the series impedance and the shunt admittance, it is not directly applicable to the usual wire line. However, complete freedom may be obtained as to the manner in which either the shunt admittance or the series impedance (but not both) vary along the line, while retaining the advantages of exponential tapering, by the expedient of assigning x to represent a suitable function of the distance along the line rather than the distance itself. If the function be analytical, the resulting differential equations are capable of solution, or in any case the performance may be determined by proper substitutions in the results given for the exponential tapering. The determination of the proper function is facilitated by noting, by integration of equations 1,

$$\left.\begin{aligned}&\text{Total series impedance from origin to point } x = \frac{Z_0}{a}(\epsilon^{ax} - 1)\\&\text{Total shunt admittance from origin to point } x = \frac{Y_0}{a}(1 - \epsilon^{-ax})\end{aligned}\right\} \quad (8)$$

Tapering of Line-Series Impedance Only

In wire-line or submarine-cable communication the most usual requirement is that in which the shunt admittance is unvarying with distance. This condition is met by equating the second of equations 8 to $Y_0l = Y_0l$. Then

$$x = \frac{1}{a}\log\frac{1}{1-al} \quad \text{or} \quad \epsilon^{ax} = \frac{1}{1-al} \quad (9)$$

in which l now represents the distance along the line, and a may be positive or negative. The line parameters follow the rule:

$$Z_l = Z_0/(1-al)^2 \text{ and } Y_l = Y_0 \quad (10)$$

The characteristic impedance at a point l, looking away from the origin, is

$$Z_c = \frac{\theta + a/2}{Y_0}\cdot\frac{1}{1-al} \quad (11)$$

where

$$\theta = \sqrt{Y_0Z_0 + a^2/4}$$

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J. W. MILNOR is a consulting engineer, Maplewood, N. J.

Inasmuch as standard definitions applicable to tapered lines have not been established, the author has used the term "characteristic impedance" as a general expression to indicate the impedance of a line of infinite length, whether the elements of the line are smooth or lumped.

case it enables the designer as well as the industrial engineer to interpret oscillograph records properly and to understand with greater assurance the performance of this important protective equipment.

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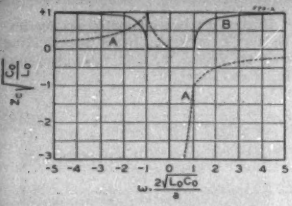

Figure 2. Characteristic impedance of smooth-taper-loaded line ignoring losses

A—Imaginary component
B—Real component

In a line of length l terminated in its characteristic impedance, the ratios of received to sent voltages and currents are

$$\frac{E_r}{E_s}=(1-al)\frac{\theta}{a}\frac{-1}{+1} \text{ and } \frac{I_r}{I_s}=(1-al)\frac{\theta}{a}\frac{+1}{+1} \quad (12)$$

Values of the sending-end impedance and of the ratio of received to sent voltage, when a line of length l is terminated in an impedance Z_r, may be obtained by inserting in equations 6 and 7 the value of x obtained from equation 9.

Lumped-Tapered Line

The foregoing equations developed for the smooth-tapered transmission line, are applicable also to the lumped-tapered line at the lower frequencies, if the line is loaded. Such a line exhibits the usual cutoff at a higher frequency. To obtain the complete solution of the lumped-tapered line it is necessary to follow a different method.

A lumped-tapered line which permits ready mathematical solution may be built up of a succession of units in which the impedances increase in geometric progression. Such a line made up of T units is shown in Figure 1. The performance is determined by solving the first unit only, which for the purpose is considered to be terminated in an impedance equal to $(1+a)Z_e$. The coefficient of tapering a of the lumped line may take any value between -1 and $+\infty$. The resulting characteristic impedance at the head of the line is

$$Z_e=\frac{\left[\frac{a}{2}\left(1+\frac{YZ}{2}\right)+\sqrt{YZ(1+a)\left(1+\frac{YZ}{4}\right)+\frac{a^2}{4}\left(1+\frac{YZ}{2}\right)^2}\right]}{Y(1+a)} \quad (13)$$

The ratios of received to sent voltages and currents across each unit in a long line are

$$\frac{E_r}{E_s}=(1+a)\frac{I_r}{I_s} \quad (14)$$

$$\frac{I_r}{I_s}=\frac{1}{\left[\left(1+\frac{a}{2}\right)\left(1+\frac{YZ}{2}\right)+\sqrt{YZ(1+a)\left(1+\frac{YZ}{4}\right)+\frac{a^2}{4}\left(1+\frac{YZ}{2}\right)^2}\right]} \quad (15)$$

Properties of the Tapered Line

The plans of tapering described herein, as well as others which may be derived from the exponential taper, are preferred forms. Aside from the comparative ease of mathematical analysis, they have the advantage that the tapering does not cause reflections of energy from points within the section, and the transfer of energy is therefore relatively efficient.

The tapering results in a transformer action which may step up or down, as is evident from equations 5, 12, 14, and 15.

A long taper-loaded line does not transmit frequencies below that where $\omega=\pm a/(2\sqrt{L_0C_0})$. This condition may set a limit to the permissible rate of taper. The characteristic impedance is largely capactitive or inductive, depending upon the sign of a, near and below the cutoff. This is illustrated in Figure 2.

Where the tapered line is lump loaded, the line, if long, behaves like a band-pass filter. The lower frequencies are lost because of the tapering; the higher frequencies because of the lumping.

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Insulation Resistance and Dielectric-Absorption Characteristics of Large A-C Stator Windings

J. S. ASKEY
MEMBER AIEE

J. S. JOHNSON
ASSOCIATE AIEE

THERE HAS BEEN considerable discussion and differences of opinion relative to the significance of insulation-resistance measurements. Numerous investigations have been made and investigators have placed varying degrees of importance on their findings.[1,2,3,4] Nevertheless, insulation-resistance measurements are used widely as a nondestructive insulation test to aid in judging the suitability of machine windings for proof test or for service. Therefore, data on average values and normal spread of the insulation resistance of new insulation are of general interest. It is the belief of the authors that in order to interpret properly insulation-resistance data, a sufficiently large number of machines must be examined to permit statistical analysis.[5,6] Furthermore, insulation studied must be segregated according to detailed construction since broad insulation classifications such as AIEE class *A* or class *B* do not specify necessarily the order of insulation resistivity. Also, the effect of other important factors such as temperature and physical-design characteristics must be considered.

Many of the data that have been presented heretofore have been obtained from machines in service. Many of these machines were of older vintage and the insulation-resistance data thus obtained therefore have been on older-type insulations as an advanced stage of the insulation life expectancy. Although these data are of value, they cannot be used properly as a basis for arriving at conclusions relative to newer-type insulation, particularly on such insulation in the earlier stages of its operating life. A need was felt, therefore, for an investigation of the insulation-resistance characteristics of new machines before leaving factory. Accordingly, data are given on approximately 1,000 new a-c synchronous and induction machines of ratings 1,000 horsepower and above.

Insulation resistance of rotating machines is known to vary over what appears to be relatively wide limits and depends on a number of factors. Certain of these factors are related to the manner in which the measurements are made, and others depend upon the nature of the insulation material and its structure. The absorptive nature of machine insulation, the effects of temperature and moisture generally are recognized. Attempts have been made to standardize testing technique, to take into account the nature of the insulating material and design characteristics of machines. This was done with the hope that when correction was made for these variables, other factors which might give a clue to insulation condition would be apparent. The ultimate aim of work of this kind is to enable one to obtain by measurements of insulation resistance and study of dielectric-absorption characteristics useful information relative to the possible existence of conditions in the insulation which might lead to eventual failure in service. Present indications are that insulation-resistance measurements are useful principally for determining moisture condition of the insulation.

Scope of Work

As a necessary preliminary to such an effort it is essential to analyze insulation-resistance data on a large number of machines to determine normal variations. These data must be taken in a consistent manner and an attempt should be made to correct for known factors which affect the insulation resistance. The scope of this work has been to obtain and analyze such data on a large number of stator windings, all of the same general class.

The slot or ground insulation of all the machines studied was mica. It was, however, applied in such a manner as to present four types of insulation as:

1. Paper-backed sheet-form mica slot insulation, with end turns insulated with treated cloth tapes.

2. Glass-backed sheet-form mica slot insulation, with end turns insulated with mica tapes.

3. Mica tape applied continuously over all portions of coils, impregnated in synthetic varnish.

4. Asphaltum-bonded mica tape applied continuously over all portions of coils, impregnated with an asphaltum compound.

In the foregoing grouping, number 1 represents class *A* insulation for which cotton tape is used for a coil binder. The other groups, 2, 3, and 4, are class *B* insulation for which coil binding tape is of fiber glass.

Temperature Corrections

There is a need for more insulation resistance–temperature data since measurements in general may be made over a wide range of temperatures and for purposes of comparison, must be referred to a common temperature. Also, present standards do not specify how insulation temperature shall be determined. Insulation-resistance measurements with insulation at a uniform temperature of 75 degrees centigrade would not be expected to be the same as measurements made with machine at an operating temperature of 75 degrees centigrade because of temperature gradient existing in the insulation. Either some uniform method of determining insulation temperature applicable to all machines or the practice of making measurements at ambient temperature conditions and correcting to a base temperature seems desirable. Examination of machine temperature–insulation resistance data available shows an approximate logarithmic variation of resistance with temperature. Synthetic varnish-impregnated mica insulation shows a change in

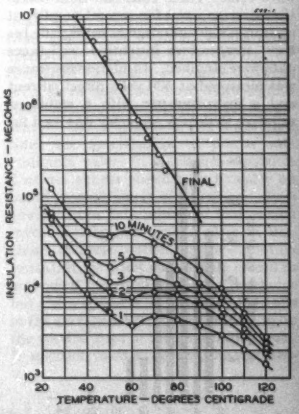

Figure 1. Temperature–insulation resistance characteristics of asphalt-bonded mica-tape insulation

Volume resistivity at 25 degrees centigrade after one minute of voltage application equals 1.7×10^9 megohm inches

Ratio-volume resistivity after ten and one minutes of voltage application at 25 degrees centigrade equals five

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J. S. ASKEY is section manager, commercial insulation section, and J. S. JOHNSON is an engineer in the development insulation section, both of the a-c generator engineering department, the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

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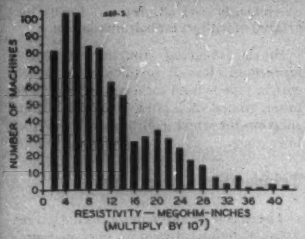

Figure 2. Frequency distribution of volume resistivity measured after one minute of voltage application, groups 1, 2, 3, and 4

Average volume resistivity equals 10.6×10^7 megohm-inches

Standard deviation is 7.4×10^7 megohm-inches

resistance from 25 degrees centigrade to 75 degrees centigrade of approximately ten to one. Asphalt-bonded continuous mica tape has a ratio of approximately 14 to 1. Since all insulation-resistance data reported here were obtained at or close to room conditions, temperature corrections were made to 25 degrees centigrade. This temperature was chosen because the temperature differences for which correction was necessary would then be small and chances of error due to inexact correction factors were minimized.

Of interest in connection with temperature–insulation resistance data are results of tests made on some asphalt-bonded mica coils. These coils had been conditioned in an oven for several months at approximately 100 degrees centigrade before temperature–insulation resistance data were obtained. Insulation resistance was measured at 500 volts direct current and a microammeter with a stabilized negative feed-back amplifier was used for current measurement. As shown in Figure 1, instead of straight logarithmic variation with temperature, a changing slope with a double inflection in the range of 40 to 80 degrees centigrade is obtained on measurements made after one to ten minutes of voltage application. Temperature–insulation resistance slope at steady-state conditions (after 15 hours of voltage application) is a straight logarithmic function as shown. Hill and Berberich reported that the ratio of ten-minute to one-minute resistivity on this type of insulation increases with temperature reaching a maximum in the range of 60 to 80 degrees centigrade and then decreases with further increase in temperature.[7]

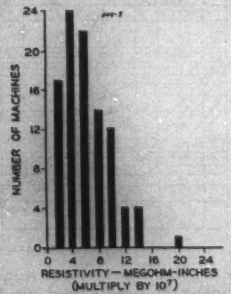

Figure 3. Frequency distribution of volume resistivity (one-minute value), group 1—class A with mica slot insulation

Average volume resistivity equals 6.0×10^7 megohm-inches

Standard deviation is 3.3×10^7 meghom-inches

Effects of Machine Size

In order to put insulation-resistance measurements of all machines on a comparable basis, effective insulation area and thickness data were obtained from the design information. Based on the effective area and thickness data, the insulation resistance of all the stator windings was expressed on a resistivity per megohm inch of insulation basis. In making the corrections for physical size, effect of leakage over end windings was neglected. All measurements were from three phases in parallel to ground.

Analysis of Data

Frequency-distribution curves of insulation resistance as measured after one minute of voltage application for all machines surveyed and groups 1, 2 3, and 4 separately are represented in Figures 2, 3, 4, 5, and 6. All resistance measurements were made at 500 volts direct current using an electronic-type megohm bridge. Distributions obtained are approximately normal.

Average resistivity and standard deviation for above groups are as follows:

Groups	Average Volume Resistivity, Megohms $\times 10^7$	Standard Deviation, Megohms $\times 10^7$	Per-Cent Dispersion
1, 2, 3, and 4	10.6	7.4	70
1	6.0	3.3	55
2	13.6	5.6	42
3	5.8	3.7	64
4	15.0	8.4	56

Groups 2 and 3 both represent data on a large number of identical machines, whereas group 4 represents machines of widely different physical size and voltage rating. Whether the relatively larger standard deviation of resistivity values of group 4 results from this fact or is naturally inherent in the type of insulation it represents is not obvious. In any event, it is evident that even after corrections are made for temperature and physical-design characteristics there is a considerable spread in the insulation resistivity. Furthermore, the average resistivities of mica insulations having somewhat different form or treated differently vary by as much as 2.5 to 1. Identical machines built in the same factory have a range of 20 to 1. The machines of group 2 were segregated into two groups according to their season of manufacture (Figure 7). This segregation narrows the dispersion somewhat but it is still relatively broad. As shown, the ratio between winter- and summer-built average is approximately two to one. That a considerable part of this spread is due to small amounts of moisture in the insulation is evident from the fact that during the summer months when moisture conditions are more severe, resistivities are appreciably lower.

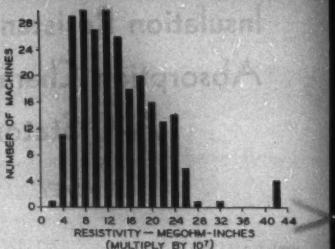

Figure 4. Frequency distribution of volume resistivity (one-minute value), group 2—class B with glass-reinforced slot insulation

Average volume resistivity equals 13.5×10^7 megohm-inches

Standard deviation is 5.6 by 10^7 megohm-inches

Dielectric-Absorption Characteristics

As is generally recognized, the insulation resistance of a stator winding will in-

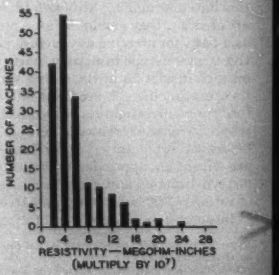

Figure 5. Frequency distribution of volume resistivity (one-minute value), group 3—class B, continuous mica tape with synthetic-varnish impregnation

Average volume resistivity equals 5.8×10^7 megohm-inches

Standard deviation is 3.7×10^7 megohm-inches

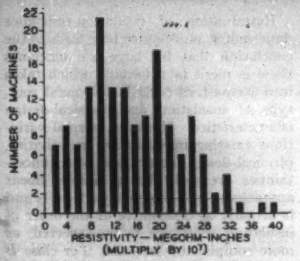

Figure 6. Frequency distribution of volume resistivity (one-minute value); group 4—class B, asphalt-bonded continuous mica tape with asphalt impregnation

Average volume resistivity equals 15.0×10^7 megohm-inches

Standard deviation is 8.4×10^7 megohm-inches

crease with time of application of voltage. This variation is caused by the electrification or "dielectric-absorption" effect in the insulation and is a function of the nature and condition of the insulation.

The shape of this absorption curve was studied on the machines surveyed and it was found that in general the first part of the curve plots as an approximate straight line on log-log paper and would therefore have an equation of the form:

$$R_t = R_1 t^n$$

where

R_t = insulation resistance after t minutes of voltage application

R_1 = insulation resistance after one minute of voltage application.

t = time in minutes

n = slope of curve on log-log paper

If t is taken as ten minutes, $n = \log \frac{R_{10}}{R_1}$

or the logarithm of the ratio of the ten

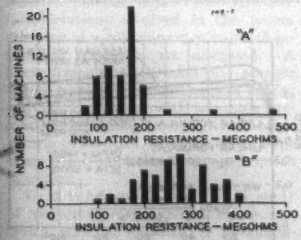

Figure 7. Frequency distribution of insulation resistance (one minute); group 2

A—Summer-built machines
Average is 146 megohms
Standard deviation is 42 megohms

B—Winter-built machines
Average is 265 megohms
Standard deviation is 80 megohms

and one minute readings of insulation resistance. The insulation resistance finally becomes constant and the slope of the absorption curve then is, of course, zero.

The ratio of the ten to the one minute insulation-resistance values at 25 degrees centigrade was obtained. Figures 8, 9, and 10 show the frequency distribution of the ratio R_{10}/R_1. Figures 2, 3, 4, 5, and 6 previously referred to give the frequency distribution of R_1. As shown in Table I, the dispersion of this ratio is considerably less than the dispersion in the value of R_1.

It is thought generally that the steepness of the slope of the absorption curve as well as the magnitude of the one-minute resistance is an indication of the dryness of a winding and that the steeper the slope the drier the insulation. Figure 11 shows the variation of the average ratio R_{10}/R_1 with insulation resistivity for machines of group 2. This group consisted of approximately 120 3,300-horsepower 2,400-volt synchronous machines having fiber-glass-reinforced mica slot insulation with impregnation in synthetic varnish. The ratio R_{10}/R_1 is seen to increase steeply at first and then flatten out and remain substantially constant over a wide range of insulation resistivity. This sort of variation seems to be characteristic at least of the insulations studied. Even coils of Figure 1 which were extremely dry, having an insulation resistivity of approximately 2×10^9 megohms, have a ratio of five at 25 degrees centigrade. Although it is true that average values of R_{10}/R_1 are constant over a wide range in resistivity, individual values vary from approximately two to six over the whole range. Figure 12 shows average absorption curves at 25 degrees centigrade plotted on logarithmic paper for ratios R_{10}/R_1 of 2, 4, and 6.

In general, study of absorption characteristics shows that new machines as built with mica ground insulation have:

1. Insulation resistivities at 25 degrees centigrade of the order of 10^7 to approximately 4×10^8 megohms.

2. Insulation resistivities in the range of one to ten minutes which vary approximately as a power function of time having an equation of the form $R_t = R_1 t^n$.

3. Ratios of R_{10}/R_1 at 25 degrees centigrade vary from one to six over the complete range of resistivity.

4. Average values of the ratio R_{10}/R_1 are substantially constant over a wide range in resistivity and decrease rather sharply for lower values of resistivity.

Minimum Insulation Resistance

Insulation-resistance measurements are used widely and are considered necessary to give assurance that the condition of insulation is such that proof voltage test can be made, to determine relative dryness of the insulation and to locate possible

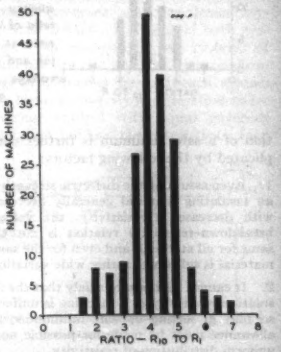

Figure 8. Frequency distribution, ratio of insulation resistance as measured after ten and one minutes of voltage application (group 2)

Average ratio is 4.0
Standard deviation is 1.0

weak spots resulting from operation or from application of proof voltage test. Insulation resistance–time curves or, correlated periodic one-minute readings on a given machine, have more significance in judging suitability of the insulation for test or operation. At the present time, the specification of precise safe minimum values of insulation resistance does not appear possible, particularly on broad general classes of insulation. As is evident from data presented here, which involves only one general class of machines and one general type of insulation (mica), there is not only a wide spread in individual values of insulation resistance but also a spread of as much as two to one in the average resistivity, depending upon the specific type of mica insulation used. In addition to these factors, the specifica-

Table I

Group	Volume Resistivity After One Minute of Voltage Application—Megohms×10⁷ at 25 Degrees Centigrade			Ratio-Volume Resistivity After 10 and 1 Minutes of Voltage Application at 25 Degrees Centigrade		
	Average	Standard Deviation	Per-Cent Dispersion	Average	Standard Deviation	Per-Cent Dispersion
2	13.5	5.6	42	4.0	1.0	25
3	5.8	3.7	64	3.1	0.9	29
4	15.0	8.4	56	2.0	1.0	38

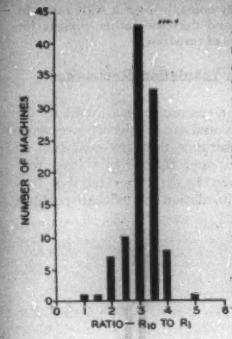

Figure 9 (left). Frequency distribution, ratio of insulation resistance as measured after ten and one minutes of voltage application, group 3

Average ratio is 3.1
Standard deviation is 0.9

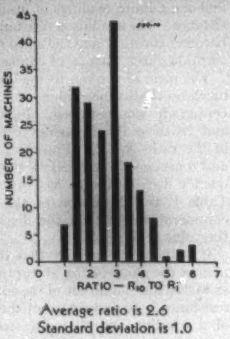

Figure 10 (right). Frequency distribution, ratio of insulation resistance as measured after ten and one minutes of voltage application, group 4

Average ratio is 2.6
Standard deviation is 1.0

tion of a safe minimum is further complicated by the following factors:

1. Even assuming the dielectric strength of an insulating material generally decreases with decrease in resistivity, the voltage breakdown-resistivity relation is not the same for all materials and even for the same material is subject to rather wide variation.

2. It cannot be assumed safely that the insulation resistivity of a machine is uniform so that in setting up safe minimums, an allowance must be made for possible nonuniform distribution of resistivity.

The present AIEE formula which gives the order of insulation resistance to be expected is:[8,9]

$$R_1 = \frac{\text{rated voltage}}{\frac{\text{rated kva}}{100}+1{,}000}$$

where

R_1 = insulation resistance at 75 degrees centigrade

Other formulas have been proposed by Wieseman which attempt to take into account type of insulation, average physical-design factors, and which give insulation resistance in terms of voltage, kilovolt-ampere rating, and speed of machines. The formula suggested for class *B* synchronous and induction machines over 1,000 kva is as follows:

$$R_1 = 0.1\,\frac{(\text{voltage}+3{,}600)\ (\text{rpm})^{1/4}}{\text{kva}^{3/4}}$$

These formulas have a more logical basis than the present AIEE formula and in a general way do take into account physical-design factors. They do not take into account in general the type of insulation, since class *A* or class *B* does not define necessarily the insulation with reference to insulation-resistivity characteristics. Various types of class *B* insulations can have different resistivities and, as is shown in this paper, even mica insulations with different fabrication as regards physical reinforcing material and treatment have different resistivities. These formulas, however, do give a better picture of the order of insulation resistance to be expected. One criticism which has been made is that the formulas are more complicated involving fractional powers, and that this would necessitate in general the reference to charts or nomographs for the calculation of resistance. For the average maintenance man, this appears to be a valid criticism.

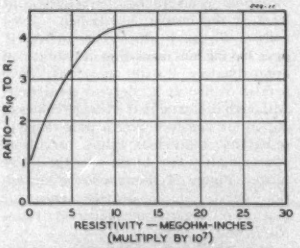

Figure 11. Average ratio of insulation resistance (ten-minute value/one-minute value) as a function of insulation resistance measured one minute after voltage application, group 2

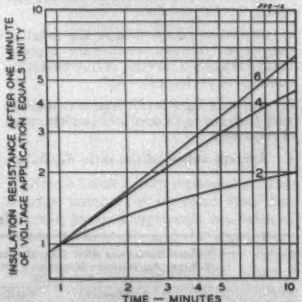

Figure 12. Average insulation-resistance–time curves as a function of ratio of insulation resistance measured after ten and one minutes of voltage application, group 2

Examination of insulation-resistance data such as is presented here leads to the conclusion that for large a-c machines there is merit in a formula which takes into account, at least in a general way, type of insulation and physical-design characteristics. However, normal variations existing in insulation resistivities, physical-design factors, and other uncertainties are such that a simpler linear approximation is completely adequate and is actually as descriptive of the order of insulation resistance to be expected, as more complicated formula. For class *B* synchronous and induction machines over 1,000 kva, the following formula is suggested:

$$R_1 = 0.006\,\frac{(E+3{,}600)\ (\text{rpm}+1{,}400)}{(\text{kva}+5{,}000)}$$

Figure 13 gives a comparison of the Wieseman formula and the suggested linear approximation.

Summary

Insulation-resistance and dielectric-absorption data have been presented which give a comprehensive picture of average and normal spread in insulation characteristics of new large a-c synchronous and induction machines having mica insulation. Dielectric-absorption characteristics have been analyzed. Average curves and normal variations are given. Ratio of insulation resistance at 25 degrees centigrade as measured after ten minutes and after one minute of voltage application has been found to increase from one, for relatively moist windings, to approximately four, for moderately dry windings, and then to remain substantially constant over a wide range in insulation resistivity. Ratio for well-dried insulation is of the same order.

Average temperature–insulation resistance characteristics for machines based on data available are given. Temperature–insulation resistance characteristics

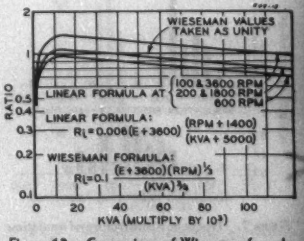

Figure 13. Comparison of Wieseman formula and suggested linear approximation

Ratio of proposed linear approximation to Wieseman formula for minimum insulation resistivity

A-c synchronous machines 1,000 kva and above

Frequency Changers—Characteristics, Applications, and Economics

S. B. CRARY
MEMBER AIEE

R. M. EASLEY
NONMEMBER AIEE

FREQUENCY CHANGERS have been discussed at various times during the past 20 years.[1,2] At the 1944 AIEE summer technical meeting there was presented a thorough analysis of the design and operating characteristics of a new 20,000-kw electronic frequency changer.[3-7] Its installation, together with increasing interest in railroad electrification for the immediate postwar period, has resulted in a renewed interest in frequency changers.

A survey[8] of a-c public-utility generating capacity as of January 1, 1941 indicates that there exist in the United States 3,250,000 kw at other than 60 cycles or about eight per cent of the 40,000,000 kw of total installed generating capacity. Of this odd-frequency capacity (other than 60 cycles) about 70 per cent is at 25 cycles. There also exist in this country 4,000,000 kw of public-utility-owned frequency-changer capacity of which about 80 per cent is 25-cycle. These odd-frequency systems are in general decreasing in size except for additions to large existing industrial 25-cycle systems, particularly steel mills, and for new capacity for a-c railroad electrification. The steel mills and railroad electrifications represent the greatest potential users of large frequency-changer equipment.

Frequency-changing equipment falls into two general classifications as shown by Table I, synchronous tie and nonsynchronous tie. The general classification, synchronous or nonsynchronous, determines the essential *system* power-flow characteristics. As shown, there are available different types of frequency-changer equipment for obtaining either type of system performance. It then becomes a matter of engineering, amenable to analysis, as to which is the best type of frequency changer to use for a given application. It is the purpose of this paper to outline the important features of the different types including relative costs and losses.

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S. B. CRARY is in the central station engineering divisions and R. M. EASLEY is in the central station divisions, General Electric Company, Schenectady, N. Y.

Synchronous Tie

The synchronous-tie type of equipment provides a link between the two systems which responds to kilowatt load changes on either system similar to that of a transmission tie line. That is, if a load change occurs on one system, a kilowatt change occurs through the frequency-changer set which is dependent upon the relative governor and supplementary-governor control regulation of both systems. For example, if two systems of equal size are tied together by a synchronous-synchronous tie and each system has the same capacity in generation under governor control with equal governor regulation and load characteristics, a load

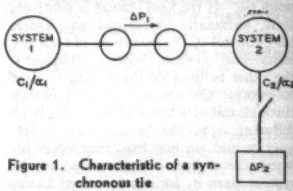

Figure 1. Characteristic of a synchronous tie

$$\Delta P_1 = \frac{\left(\frac{C_1}{\alpha_1}\right)}{\left(\frac{C_1}{\alpha_1}\right)+\left(\frac{C_2}{\alpha_2}\right)} \Delta P_2$$

where

α_1 = system speed regulation of system 1
α_2 = system speed regulation of system 2
C_1 = generating capacity of system 1 in kilowatts
C_2 = generating capacity of system 2 in kilowatts

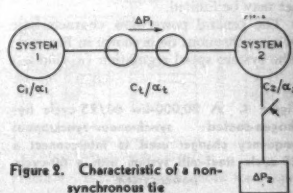

Figure 2. Characteristic of a nonsynchronous tie

$$\Delta P_1 = \frac{\left(\frac{C_1}{\alpha_1}\right)}{\left(\frac{C_1}{\alpha_1}\right)+\left(\frac{C_2}{\alpha_2}\right)+\left(\frac{C_1}{\alpha_1}\right)\left(\frac{C_2}{\alpha_2}\right)\left(\frac{\alpha_t}{C_t}\right)} \Delta P_2$$

where

α_1 = system speed regulation of system 1
α_2 = system speed regulation of system 2
α_t = speed regulation of tie
C_1 = generating capacity of system 1 in kilowatts
C_2 = generating capacity of system 2 in kilowatts
C_t = tie capacity in kilowatts

of well-dried asphalt-bonded mica insulation are given as a function of various times of voltage applications. Indications are that variation of absorptive current with temperature for asphaltic-bonded mica insulation does not even approximate a simple logarithmic function. Considerations involved in the proper selection of a safe minimum value of insulation resistance are discussed. A linear formula which takes into account effects of speed, kilovolt-ampere rating, and voltage rating, with adequate precision when consideration is given to other variations involved, is suggested for large class *B* a-c induction and synchronous machines.

Work is being continued on the study of variations involved and significance which may be attached to insulation-resistance measurements. Others should be encouraged to engage in similar activity with emphasis on obtaining a sufficient amount of data to permit statistical evaluation of results since spot readings have proved of little value in the past. Such data, obtained from a number of manufacturers and correlated with periodic data obtained on machines during service life, would aid in a better understanding of the nature and significance of insulation resistance measurements.

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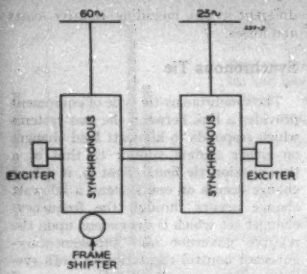


Figure 3. Synchronous–synchronous

increase on one of the systems will result in about 50 per cent of the load increase being transferred through the synchronous tie. If the load change is relatively slow, automatic or manual supplementary control of the governors of both systems—one system holding frequency, the other holding tie load—may be used to control the amount of load change through the synchronous tie. This is no different from the present use of frequency and tie line load controllers for transmission lines. If the ratio of the system sizes is, for example, ten to one with the same percentage system speed regulation for each system, the smaller system representing the 25-cycle system, and the larger system the 60-cycle system, a load change on the 25-cycle system will result in about nine-tenths of the load change being transferred through the synchronous frequency-changer set to the 60-cycle system. However, if there is in the smaller system sufficient generating capacity provided with adequate supplementary control, the load change through the synchronous-tie frequency-changer set may be limited.

The general power-flow characteristic of a synchronous tie is shown in Figure 1. The system speed regulation (α_1 and α_2) may be taken as either the inherent governor regulation or the governor supplementary control regulation depending upon the time after the load change has occurred. If the change is relatively rapid, the power flow before the governors have had time to effect a change can be determined simply by

$$\Delta P_1 = \frac{C_1}{C_1 + C_2} \Delta P_2$$

when the same effective inertia per kilowatt of generating capacity is assumed.

The control of power through the synchronous tie is determined by the relative generating capacity under governor control of the two systems, the size and rate of application of a load change, and whether or not supplementary control is used for control of the frequency-changer load.

Where the loads are not highly variable, it has been found possible to use synchronous-tie frequency-changer capacity of only ten per cent of the smaller system and to obtain satisfactory operation by manual control or load dispatching of the governors of the smaller system. However, when the loads are large and vary rapidly, it becomes more difficult to keep a synchronous tie in synchronism, particularly one whose capacity is small relative to the magnitude of the suddenly applied load change. For any given case, performance may be predetermined with good engineering accuracy by analysis.

Nonsynchronous Tie

The nonsynchronous tie is one which is capable of confining large and rapid load changes to one system. If the load variations are large so that they would be objectionable, for example, to the larger system, they may be confined to the smaller system by a nonsynchronous tie. On the other hand, the smaller system which has the objectionable load is subjected to a considerably larger frequency deviation and greater change in its generator loading than if the tie were synchronous. Although operating companies object to large rapidly varying loads, the design of interconnected systems has progressed so as to permit taking on these varying loads with less and less difficulty.

The characteristic of an asynchronous tie is shown in Figure 2. The different types of frequency changers are characterized by a different speed regulation α_t. The synchronous tie can be represented as a special case with $\alpha_t = 0$.

Summarizing, there are these essential and important differences between the synchronous and the nonsynchronous ties:

(*a*). With the synchronous tie, the rapidly varying load changes are shared by both systems, the larger system taking the greater part of the variation.

(*b*). With the nonsynchronous tie, the rapidly varying load changes can be confined to where they originate. The type of nonsynchronous tie determines the degree of this isolation for different rates of load application.

An essential characteristic to keep in mind is that it is simpler to parallel synchronous-tie equipment with the same type of tie capacity. Similarly, the use of nonsynchronous tie equipment tends to perpetuate the use of this equipment when additional tie capacity is needed at a future time, since it is desirable to keep the inherent speed regulation of the paralleled ties similar. This is particularly true for rapidly varying loads.

Essential Features

The essential features of the five types of frequency changers listed in Table I are as follows:

Synchronous–synchronous[9, 10] (synchronous tie). Figure 3.

(*a*). This type consists of a synchronous motor and synchronous generator with their individual exciters. It may be provided with a pilot exciter in the larger sizes and may have a starting motor. For 60 to 25 cycles the speed is 300 rpm, while for 60 to 50 cycles the speed may be 600 or 300 rpm.

(*b*). A frame shifter is usually provided on the 60-cycle end for parallel load division between frequency-changer sets. Frame

Figure 4. A 20,000-kw 60/25-cycle hydrogen-cooled synchronous-synchronous frequency changer used to interconnect a 25-cycle steel-mill system with a 60-cycle power system

Figure 5. A 30,000-kw 60-cycle three-phase to 25-cycle single-phase air-cooled synchronous-synchronous frequency changer used to supply a single-phase 25-cycle railroad system from a 60-cycle power system

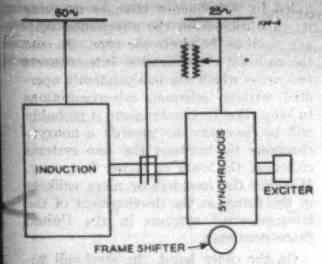


Figure 6. Induction frequency converter

shifters can be provided which allow for a shift of 16 to 24 mechanical degrees for a 300-rpm set. This is sufficient range for synchronizing and paralleling. The angle can be changed over its complete range at a rate of one mechanical degree (12 electrical degrees) in nine seconds.

(*c*). Voltage regulators and excitation systems are usually provided so as to obtain sufficient pull-out torque and kilovars to meet normal and emergency system requirements for the maintenance of system voltages. Under regulator control the pull-out power exceeds considerably the nominal synchronous-machine pull-out power, approaching 200 to 300 per cent of normal depending on system conditions.

(*d*). Sufficient kilovar capacity can be provided to meet the load and system requirements at a relatively low cost per kilovar.

(*e*). A single-phase generator may be provided at one end to supply single-phase load. In this case the stator of the single-phase generator is spring-mounted to reduce the transmission of vibration to the foundation and to reduce the magnitude of the alternating component of stator-bolt stresses.

Figure 4 shows a 20,000-kw 60/25-cycle hydrogen-cooled synchronous–synchronous frequency changer used to interconnect a 25-cycle steel-mill system with a 60-cycle power system.

Figure 5 shows a 30,000-kw 60-cycle three-phase to 25-cycle single-phase air-cooled synchronous–synchronous frequency changer used to supply a single-phase 25-cycle railroad system from a 60-cycle power system.

Induction frequency converter–synchronous[14] (synchronous tie). Figure 6.

(*a*). This type consists of an induction machine for the 60-cycle end and a synchronous machine for the 25-cycle end which has 35/60 of the kilowatt capacity of the 60-cycle induction machine. The rotor of the induction machine is connected by slip rings through a transformer to the 25-cycle system. This provides an electrical as well as mechanical tie between the 60- and 25-cycle systems. A direct-connected exciter is usually provided for the synchronous machine. The 60–25-cycle set has a speed of 300 rpm.

(*b*). The synchronous machine may be used to provide kilovars and regulate the voltage at the 25-cycle end. A tap-changing transformer may be used for a limited amount of regulation of the 60-cycle bus voltage.

(*c*). The kilovar capacity of this set is limited compared with the synchronous–synchronous set. Under fault or emergency conditions, however, this set is able to transfer kilovars from one system to another. It is, therefore, well suited for connecting together closely coupled systems so that one system can support the other in case of a fault or overload. This type of frequency changer found application in the days of synchronous converters and before generator voltage regulators were so generally used.

(*d*). This type of set may be provided with a frame shifter for parallel load division.

(*e*). It is not well suited for supplying single-phase loads as a phase unbalance would be reflected into the three-phase system.

Figure 7 shows a 40,000-kw 60/25-cycle air-cooled induction frequency converter used to interconnect 60- and 25-cycle three-phase metropolitan systems.

Figure 7. A 40,000-kw 60/25-cycle air-cooled induction frequency converter used to interconnect 60- and 25-cycle three-phase metropolitan systems

Table I. Classification of Important Types of Frequency Changers

Type	Approximate Kilowatt Capacity Installed in United States Since 1928
Synchronous tie	
Synchronous–synchronous	585,000
Induction frequency converter—synchronous	15,000
Nonsynchronous tie	
Induction–synchronous load-regulating	110,000
Electronic load-regulating	26,600
Induction-synchronous	Negligible

Induction–synchronous load-regulating[11,12,13] (nonsynchronous tie). Figure 8.

(*a*). This type of set consists of a synchronous machine connected to one system with an induction machine connected to the other system. The induction machine receives slip-frequency excitation from a regulating exciter which is in turn excited from a frequency-changing exciter. The induction end may be at either frequency. This type of set has, in general, the same speeds as the synchronous–synchronous sets for a given frequency ratio, although it is not as rigidly limited in possible speeds. Installations up to 10,000 kw capacity have been made with rated speeds in the range of 500 to 514 rpm.

(*b*). Control of voltage and kilovar supply can be obtained at either end. It is somewhat easier to obtain low power factor at the synchronous end.

(*c*). Load control can be made sufficiently fast to meet the most severe requirements usually met in practice.

(*d*). It can be used to supply single-phase load from the synchronous end.

(*e*). Controlled frequency range is usually about plus or minus two per cent.

Figure 9 shows a 10,000-kw induction synchronous load-regulating air-cooled 60/25-cycle frequency changer set used for supplying an industrial 25-cycle system.

Electronic load-regulating[3–7] (nonsynchronous tie). Figure 10.

(*a*). This type of frequency changer consists of rectifier and inverter elements with transformers, switches, and control.

(*b*). Load through the frequency changer can be controlled so as to hold power through the frequency changer with rapid changes in system frequency and therefore this equipment is capable of isolating load changes of one system from another.

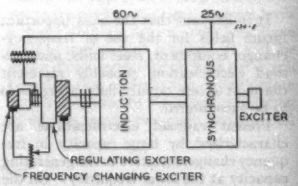


Figure 8. Induction–synchronous load-regulating

(*c*). System kilovar requirements as well as the excitation kilovar requirements of the frequency changer set must be supplied by synchronous condensers or from system sources.

(*d*). Because this set is excited from a system it requires system synchronous capacity to maintain the voltage and frequency within limits for proper rectifier and inverter excitation.

(*e*). Recent improvements include use of

Figure 9. A 10,000-kw induction-synchronous load-regulating air-cooled 60/25-cycle frequency changer set used for supplying an industrial 25-cycle system

high-voltage pentode ignitrons[4] with automatic clearing and re-energization following inverter "shoot throughs."

(*f*). In case of power failure on one or both systems, the service may be quickly re-established by reclosing the line circuit breakers, provided the system voltages have returned to the range required for commutation. No resynchronization is needed as with many types of rotating equipment.

(*g*). This type of frequency changer, being a static equipment, is well suited to a design of an unattended station.

Figure 12 of reference 3 shows a cross-section elevation af a 20,000-kw electronic load-regulating frequency changer.

Induction-synchronous (nonsynchronous tie). Figure 11.

(*a*). Consists of induction motor with a synchronous generator and exciter.

(*b*). Allows for a departure in frequency from one system to another with change in loading. Load transfer depends on departure from synchronous-frequency ratio and is not independent as in case of II-1 and II-2 types.

(*c*). Induction motor requires system kilovars for excitation.

Important Applications

It so happens that the most important future fields for the use of frequency-changer equipment, steel mills, and railroad electrification, probably represent the most severe rapidly fluctuating loads to be encountered.

Present railroad electrifications are characterized by large capacity in frequency changers relative to the generating capacity at the lower frequency. On the other hand, the steel-mill 25-cycle system may be relatively large compared to the frequency-changer capacity. This may be said to be the essential difference between these two types of frequency-changer applications aside from the distinction that the railroad electrification is usually single-phase. The distance traversed by railroad as compared with the concentration of load and availability of waste heat energy in the steel mill is one of the essential reasons why it becomes more economical in the former case to use a large capacity in frequency-changer sets relative to generating capacity at the lower frequency. In the case of the railroad this allows a better utilization of the railroad kilowatt diversity by high-voltage transmission of the power with the location of the 25-cycle supply not being dependent on sites having generating plant facilities.

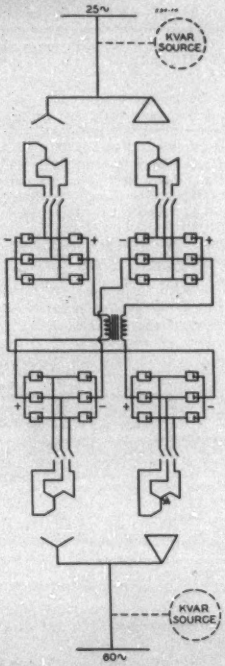


Figure 10. Electronic load-regulating

In the case of railroad electrification which uses a large frequency-changer capacity relative to the generation at the lower frequency, there is no particular problem in keeping the sets in synchronism in spite of the severe railroad load changes provided the 60-cycle supply system has adequate transmission-line capacity. The synchronous–synchronous set has the advantage of being separately excited by direct-connected exciters. This provides better voltage conditions along the 25-cycle transmission system following load changes than can be provided by a frequency changer receiving its excitation from the alternating voltage, such as the electronic type. In case the railroad electrification interconnects two areas which are independently operated, without adequate interconnections to keep them in synchronism, it probably will be necessary to provide a nonsynchronous tie between the two systems either at the lower or higher frequency. However this case will be more unlikely in the future as the development of the interconnected systems in the United States continues.

On the other hand, the steel-mill 25-cycle system may be relatively large compared with the magnitude of the load change that is suddenly applied which in turn may be large compared with the frequency-changer capacity, particularly if there is a large strip mill. This case represents the most severe type for the use of a synchronous tie, since the total load change, if the 60-cycle system is large, will be practically all transmitted through the synchronous tie. In the case of a steel mill this load may be suddenly applied and removed in a few seconds (20,000 to 30,000 kw may be applied in 8 to 12 seconds), so that supplementary control of the 25-cycle steel-mill generation would, only with difficulty, regulate the flow of power through the tie. This is an ideal case for making use of the rotating energy of the system if a relatively large frequency change can be tolerated on the 25-cycle system. Also, a small amount of the total load may be controlled by allowing the frequency to change within the control limits of the nonsynchronous tie, when the 25-cycle system includes a large rotating load. This case represents, therefore, an ideal situation for the use of a nonsynchronous tie. Either the induction synchronous load-regulating or electronic type may be used, whichever most satisfactorily meets the requirements of the particular case. The electronic frequency changer's requirement of receiving its excitation from the a-c supply system need not be a limitation in this case, although it would be in the case of railroad electrification where there does not exist a relatively cheap source of kilovar capacity.

For conditions as outlined the large strip-mill load of a steel mill because of its character may be interconnected with a large system by a nonsynchronous tie with the principal advantage of insulating the 60-cycle system from the load changes of the steel mill. On the other hand, the railroad electrification can be supplied through a synchronous tie provided, of course, that the 60-cycle supplying systems are sufficiently well interconnected so as to remain in synchronism.

Economic Discussion

It seems in order to consider these same classes of equipment from an eco-

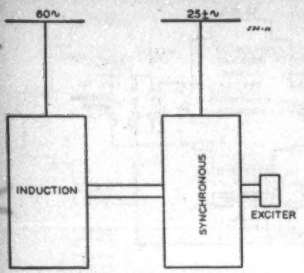


Figure 11. Induction–synchronous

nomic standpoint and an attempt is made herein to cover such factors as relative first costs and losses. Such factors as costs of foundations, costs of buildings, and the amount of first cost to be considered as offset by evaluated loss savings may vary within rather wide limits, depending on local conditions, customer's ideas as to types of structures, load factors, and so forth. Therefore, any figures set up by a manufacturer are open to question and can be right only for one set of conditions.

It is expected that the cost of installation and foundation should favor the electronic equipment. If, however, the latter requires the use of synchronous condensers for system excitation the total installation cost with the electronic frequency changer may be higher than with a rotating equipment.

Since it is felt that the difference in switchgear will not decisively affect the comparisons, it will be left out of this discussion for the sake of simplifying the picture.

It is further recognized that within the scope of this paper it is impossible to cover completely all variations which may be encountered in actual practice. This refers to cases where excess kilovars may be available, where various types of starting are required for rotating equipment, and so forth. Such data as are given hereafter will be given in such detail as to permit considerable flexibility in applying them to individual cases in order to make them most useful.

Figure 12 has been prepared to show the relative costs of the various types of frequency-changer sets at 20,000 kw for operation between 13,800-volt three-phase 60-cycle bus and 13,800-volt three-phase 25-cycle bus. It is assumed that power flow in either direction will be required with full set kilowatt output, but that the generators of rotating equipments will be permitted to operate at increased power factor when motoring in order to stay within rated kilovolt-amperes. In representing the various pieces of equipment going into the makeup of the rotating sets, the percentage is shown adjacent thereto in order to give a comparison. Similar percentages are not shown for the electronic set because it is expected that these may change appreciably relative to the rotating sets. Such figures, however, can be made available by the manufacturers when needed on a current basis. Thus it is possible from the figures to arrive at different combinations more applicable to individual problems. It will be noted that the synchronous–synchronous set has been chosen as 100 per cent (this without the starting motor included) and all other equipment is shown on this same base. A starting motor can be added to this set as shown in part A of Figure 12 at 3.4 per cent, or the coolers, exciters, and frame-shifting device may be omitted at the figures indicated.

Transformers for stepping up from 13.8 kv can be added directly to the rotating equipment at either end. At a capacity of 20,000 kw for the electronic equipment and below high-voltage values of 138 kv, it will be somewhat cheaper to combine these step-up transformers with the transformer reactor combination already included for 13.8 kv. At this kilowatt capacity the net effect of requiring transformers on the 60-cycle end of the rotating equipment will be to increase its cost relative to that of the electronic equipment approximately ten per cent at 23 kv and 1.0 per cent at 115 kv. Adding transformers to the 25-cycle end will result in differences about 50 per cent more than these. Larger sets will be slightly more favorable than this to the rotating equipment and smaller ones to the electronic.

Synchronous–Synchronous (Air-Cooled)

The synchronous–synchronous set shown in Figure 12A consists of the following:

One 25,000-kva 0.8-power-factor 13,800-volt three-phase 25-cycle synchronous generator.

One 23,500-kva 0.9-power-factor 13,800-volt three-phase 60-cycle synchronous motor.

One generator exciter with motor-operated rheostat.

One motor exciter with motor-operated rheostat.

One common pilot exciter with manually operated rheostat.

Surface air coolers (no duct work) and frame-shifting device for the 60-cycle unit.

This represents 100 per cent.

The starting motor shown as an added item at 3.4 per cent is a low-voltage machine (2,200 volts or less).

Synchronous–Synchronous (Hydrogen-Cooled)

The hydrogen unit shown in Figure 12B has main machines of the same rating as the air-cooled unit (although of smaller physical dimensions in order to take advantage of improved cooling with hydrogen as the cooling medium), does not have a frame-shifting device, but does have built-in surface gas coolers. It will be minus direct-connected exciters but it will be noted that an induction-motor-driven exciter set is shown separately, consisting of driving motor, two main exciters, and

Table II. Summary of Frequency-Changer Characteristics

		Type of Frequency Changer				
		Air-Cooled Synchronous–Synchronous	Induction Frequency Converter—Synchronous	Induction–Synchronous Load-Regulating	Electronic Load-Regulating	Induction–Synchronous
Type of tie		Synchronous	Synchronous	Nonsynchronous	Nonsynchronous	Nonsynchronous
Effective kilowatt–speed regulation of tie	Sudden changes	0	0	0.005 to 0.01	0 to ∞	0.005 to 0.01
	Rapid changes	0	0	0 to ∞	0 to ∞	0.005 to 0.01
	Slow changes †	0	0	0 to ∞	0 to ∞	0.005 to 0.01
	Slow changes ‡	0 to ∞	0 to ∞	0 to ∞	0 to ∞	0 to ∞
Excitation		Independent, both ends	Independent, one end; system, one end	Independent, one end; system, one end	System, both ends	Independent, one end; system, one end
Relative cost (20,000 kw)**		1.0	1.84	1.30	*	
Relative full-load losses (20,000 kw)***		1.0	1.47	1.65**		

† Without supplementary governor control of system prime movers.
‡ With supplementary governor control of system prime movers.
* Greater than Scherbius plus transformers.
** Includes synchronous condensers for kilovar supply.
*** Three-phase 60-cycles to three-phase 25 cycles.

pilot exciter suitable for supplying both main exciters. It will be noted that the total for frequency changer set and exciter set is 108.2 per cent.

Since a starting motor would unduly complicate the hydrogen enclosure a starting autotransformer is shown on the chart at 2.6 per cent as a separate item. It will be noted that this has a price of the same order of magnitude as the starting motor.

Synchronous–Synchronous (Air-Cooled Single-Phase)

Figure 12C shows a synchronous–synchronous set rated and furnished same as the unit shown in A except that the 25-cycle generator is a single-phase unit having special amortisseur winding and spring mounting to damp out mechanical vibrations due to the pulsations of the single-phase current. The third leg of the winding is omitted as is usual. It will be noted that this equipment has a price of 120.5 per cent. A starting motor or autotransformer may be added.

Induction–Synchronous Load-Regulating

Figure 12D shows the variable-ratio rotating equipment and again the kilovolt-amperes, voltage, and power-factor ratings are the same as for Figure 12A, the a-c excitation equipment being designed to give 0.8 power factor overexcited. This equipment also provides for a limiting relative spread between 25- and 60-cycle system frequencies of plus or minus one per cent. Additional spread will increase the cost. Blowers are required for properly ventilating the induction machine and these are included.

The equipment has a price of 129.7 per cent. A starting motor or autotransformer may be added.

Induction Frequency Converter—Synchronous

Figure 12E shows the induction frequency converter-synchronous set. The 60-cycle induction unit is designed for unity power factor but there is included a synchronous condenser to bring this to 0.9 power factor. Therefore the over-all equipment is again comparable with Figure 12A since the 25-cycle generator is made 0.52 power factor to bring this end of the equipment to 0.8 power factor over-all.

The total is 135.4 per cent. A starting motor or autotransformer may be added.

Electronic Load-Regulating

Figure 12F shows the electronic equipment consisting of the necessary 25- and 60-cycle transformers, the electronic converter, or rectifier, and the inverter, together with synchronous-condenser equipment to correct the 60-cycle power factor to approximately 0.9 overexcited and the 25-cycle power factor to approximately 0.8 overexcited. (There is in addition sufficient kilovar capacity to allow for approximately a five per cent drop in voltage on either system.) This equipment is actually two 10,000-kw units and therefore for some installations may have definite operating advantages in that either half may be shut down and the other operated independently.

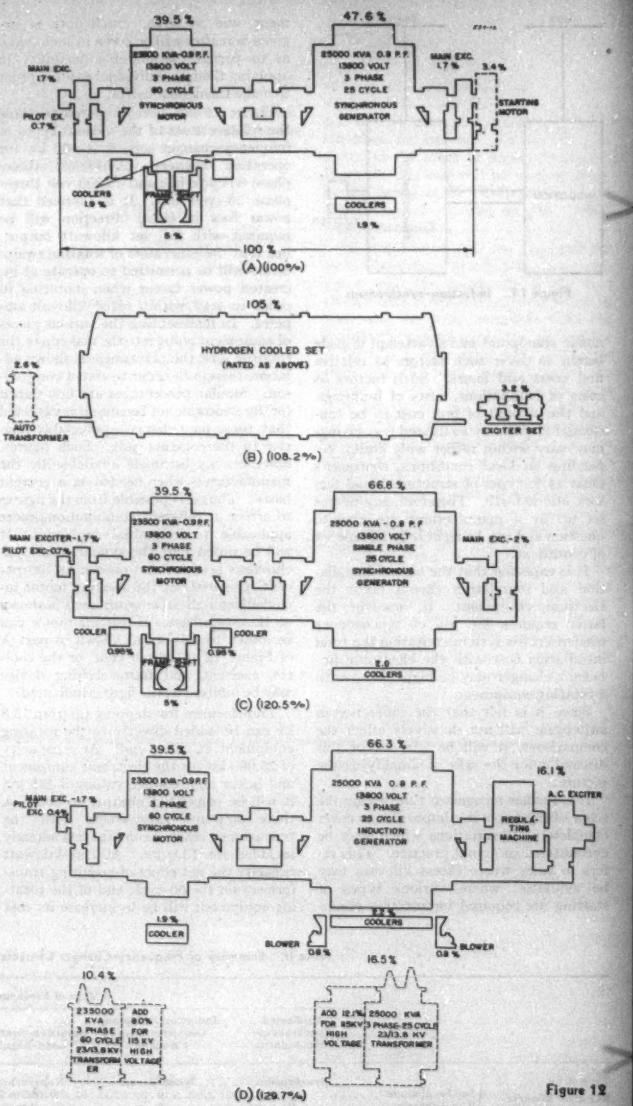
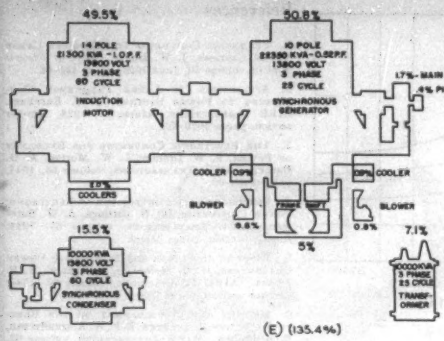


Figure 12

It is recognized that the power factor correction as provided may not be required but this is included to bring all equipments to a comparable basis. At the present time, if it is assumed that the necessary 25- and 60-cycle reactive kilovolt-amperes is available and need not be charged against the electronic equipment,



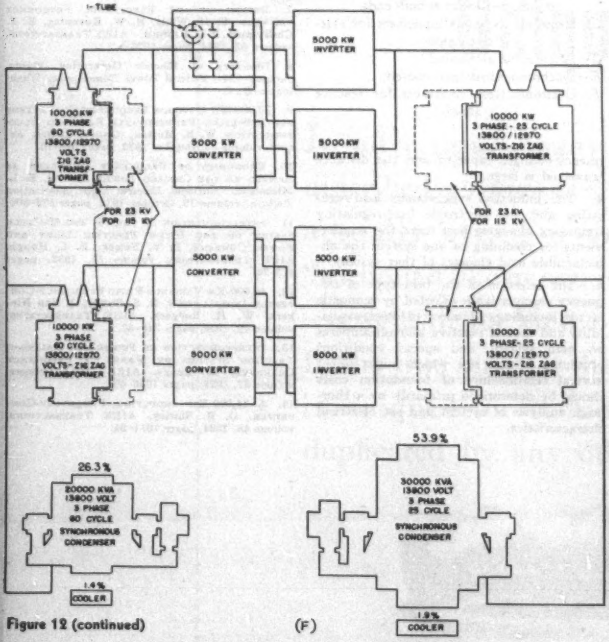

I-TUBE
5000 KW INVERTER
10000 KW 3 PHASE 60 CYCLE 13800/12970 VOLTS ZIG ZAG TRANSFORMER
9000 KW CONVERTER
9000 KW INVERTER
10000 KW 3 PHASE - 25 CYCLE 13800/12970 VOLTS-ZIG ZAG TRANSFORMER
FOR 23 KV
FOR 115 KV
5000 KW CONVERTER
5000 KW INVERTER
10000 KW 3 PHASE 60 CYCLE 13800/12970 VOLTS-ZIG ZAG TRANSFORMER
9000 KW CONVERTER
9000 KW INVERTER
10000 KW 3 PHASE-25 CYCLE 13800/12970 VOLTS-ZIG ZAG TRANSFORMER
26.3%
20000 KVA 13800 VOLT 3 PHASE 60 CYCLE SYNCHRONOUS CONDENSER
1.4% COOLER
53.9%
30000 KVA 13800 VOLT 3 PHASE 25 CYCLE SYNCHRONOUS CONDENSER
1.9% COOLER
(F)

Figure 12 (continued)

the cost of the electronic equipment and transformers is greater than that of the rotating variable-ratio equipment plus its transformers.

It might be noted that if reverse flow of power is not required a saving in the converter equipment is possible. Such a condition is rarely visualized in system interconnection but might be reasonable in supplying an isolated load.

It should be kept in mind that the engineering problems involved in design and manufacture of rotating equipment have had the benefit of many years of study so that the probabilities of substantial cost improvements are not very great. On the contrary, the electronic equipment is at a much earlier stage of development. Therefore, it is fair to assume that substantial improvements and cost reductions may be possible in this type of equipment in the near future.

Comparative Costs and Losses Versus Capacity

At the present it is believed that rotating equipment will be even more advantageous in sizes above 20,000 kw and somewhat less so in the smaller sizes, with electronic most competitive at about 5,000-kw sets.

Figure 13 is largely self-explanatory. Again the three-phase to three-phase air-cooled synchronous–synchronous set is considered 100 per cent. Shown thereon are relative per cent full load losses over the range of 5,000 kw to 35,000 kw for synchronous–synchronous, synchronous–synchronous hydrogen-cooled, rotating variable-ratio, and electronic frequency-changer equipment. It will be noted that for the electronic a curve is shown for the equipment itself exclusive of condenser losses and at 20,000 kw a higher point which includes losses in condensers used to correct power factor to overexcited values comparable to those of the rotating sets.

Figure 14 shows relative per cent no-load losses for the same sets.

If it is assumed that 23-kv transformers are required on both ends of a 20,000-kw rotating variable-ratio frequency-changer set the relative per cent full-load losses including transformer losses would increase to 1.79 and the no-load to 0.794. These points are shown on the figures.

In evaluating losses some consideration may also need to be given to cooling-water requirements. Lower losses mean less cooling water if coolers are used and may be an economic factor if water is purchased.

It is recognized that there are other ex-

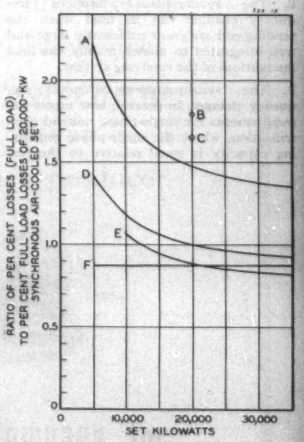


Figure 13

A—Variable ratio—rotating
B—Variable ratio—rotating, including 23-kv transformer losses at both ends
C—Electronic including equipment for reactive supply
D—Synchronous air-cooled
E—Synchronous hydrogen-cooled
F—Electronic (less equipment for reactive supply)

penses which manufacturers are not in a position to evaluate definitely, such as operation, maintenance, supervision, and, in the ease of the electronic equipment, tube replacement. Experience with these particular tubes is not sufficient to give actual operating data on life. For several years similar heavy-duty power tubes have been sold with a three-year operating warranty and it is expected that experience with these tubes will be comparable or in the order of three to five years' operating life.

The electronic frequency changer described in references 3, 4, 5, and 7 illustrates a case most favorable to this type of equipment: the power supplies were 69 kv and 44 kv, respectively; sufficient kilovars were already available at both the 60-cycle and 25-cycle systems; an unattended station was called for; because of flood conditions in the proposed location the frequency changer had to be located high above ground, a fact which favored a static equipment. These conditions may or may not be duplicated elsewhere and, therefore, the choice can be made only individually for each case.

Conclusions

1. There are now available several different types of frequency changers with a wide range of characteristics (Table II), which have been proved in service to meet the requirements of differing applications.

2. The synchronous–synchronous frequency changer can be used when the sending-end system is sufficiently large and well integrated to absorb readily the load fluctuations of the receiving system.

3. The synchronous–synchronous frequency changer, in general, best meets the requirements for single-phase railroad electrification, where the single-phase generating capacity is small relative to the frequency-changer capacity and the distance traversed is large.

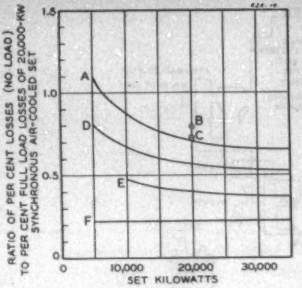


Figure 14

A—Variable ratio—rotating
B—Variable ratio—rotating, including 23-kv transformer losses at both ends
C—Electronic including equipment for reactive supply
D—Synchronous air-cooled
E—Synchronous hydrogen-cooled
F—Electronic (less equipment for reactive supply)

4. The induction synchronous load-regulating and the electronic load-regulating frequency changers best meet the requirements for confining to one system the objectionable load changes of that system.

5. The selection of the best type of frequency changer while affected by economic factors including evaluation of losses, availability and cost of reactive kilovolt-amperes on each system, and special conditions obtaining at the site which might affect normal relationships of foundation costs should be determined primarily by a thorough analysis of system and set electrical characteristics.

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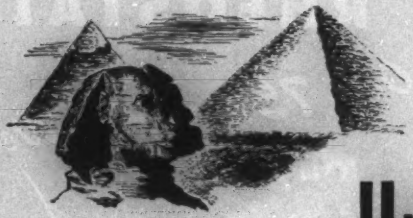

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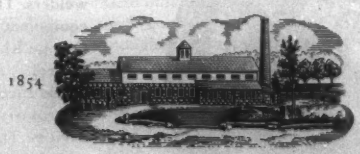

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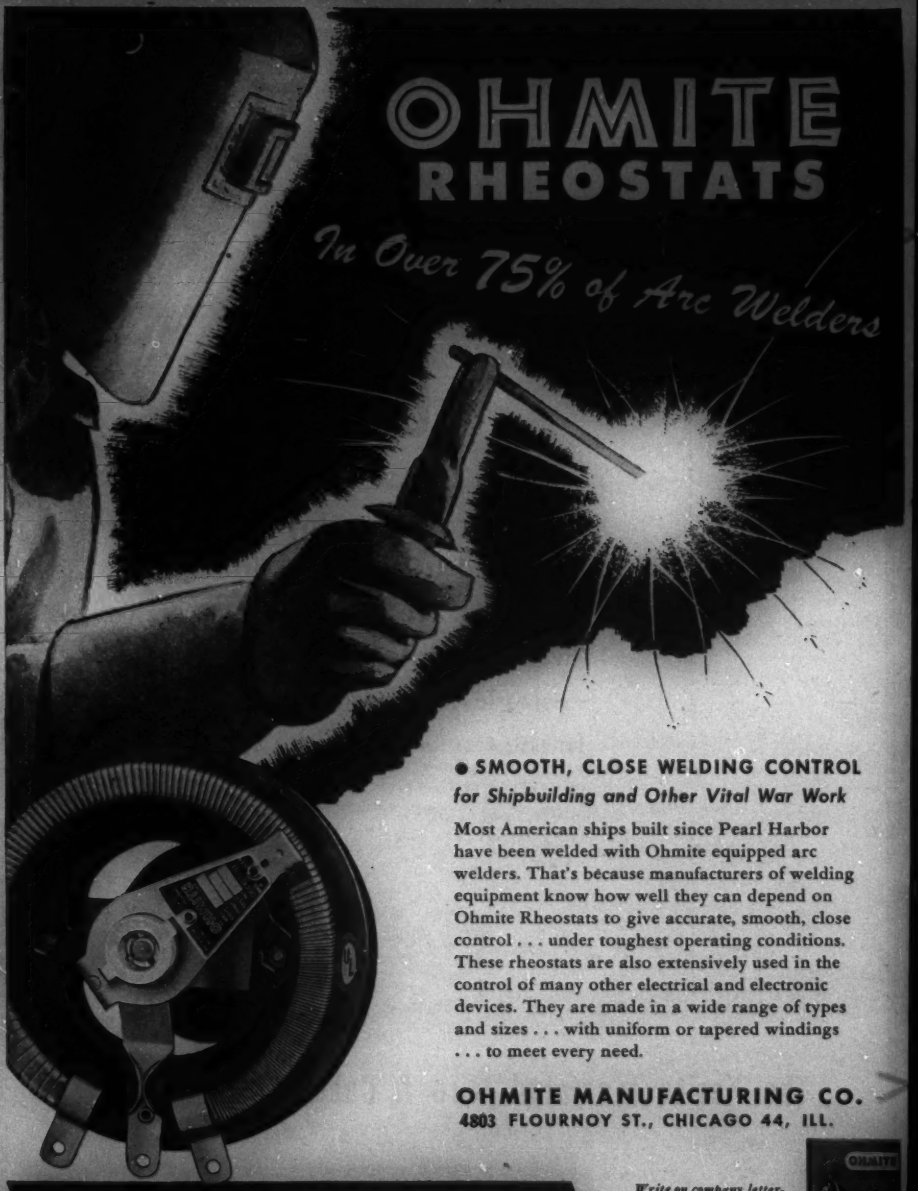

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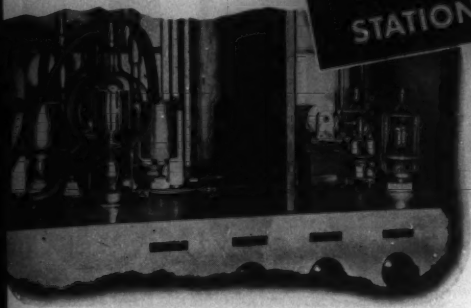
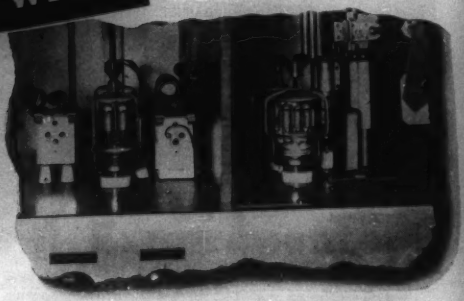


The video transmitter operates at 61.25 megacycles; peak power output is 4 KW which provides a television service throughout metropolitan Chicago and reaches suburbs out to 35 miles or more.



Eimac 152-T's are used in the modulated stage and 304-T's in the first Class B linear amplifier of the video transmitter.

E. F. Cawthon and W. R. Brock are operating the station which has been broadcasting television programs with the present equipment since 1942 and began operation on a commercial schedule in October, 1943.

Grid modulation is employed at WBKB and a broad band of frequencies must be passed in all stages following the modulated amplifier. Multiple-tuned resistance loaded coupling circuits are used between stages.

Performance, stability, dependability are good reasons why Eimac tubes are to be found in the key sockets of the outstanding new developments in Electronics. Balaban & Katz, owners of television station WBKB of Chicago, offer potent confirmation of the fact that Eimac tubes are first choice of leading Electronic Engineers the world over.

FOLLOW THE LEADERS TO

Eimac TUBES

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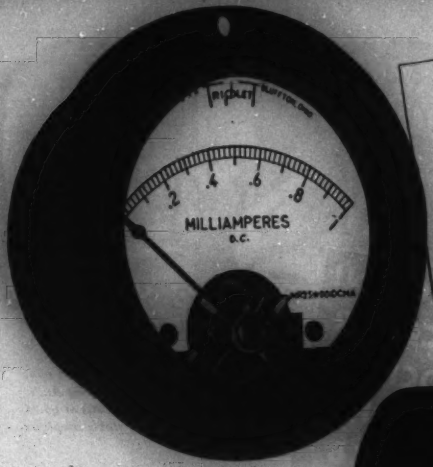
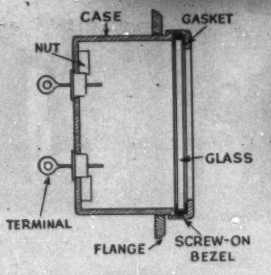
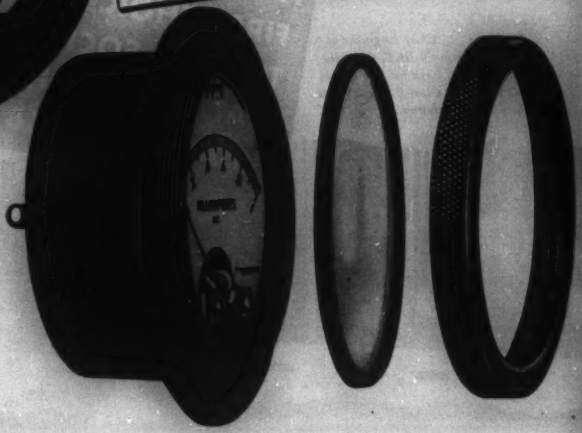


INTRODUCING THE NEW TRIPLETT LINE OF HERMETICALLY SEALED INSTRUMENTS





ALL THE FEATURES of STANDARD INSTRUMENTS RETAINED

Withstands submersion tests at 30 feet

A screw-on bezel provides uniform pressure for hermetically sealing the glass to the case. The gasket is pressed into every crevice around the edge of the glass and the top of the case, where the permanent seal is made.

Tempered glass window and ceramic sealed terminals are used.

The knurled screw type bezel permits servicing when necessary and resealing without replacing a single part or the use of special tools or equipment.

Complete dehydration of the interior is readily accomplished by recognized temperature difference method (the bezel loosely attached for the escape of all moisture, after which the bezel is tightened to make the permanent seal). Interior is completely dry at slightly above atmospheric pressure.

These instruments comply with thermal shock, pressure and vibration tests. They also are resistant to corrosion. Instruments conform to S.C. No. 71-3159 and A.W.S. C-39.2-1944 specifications.

Furnished in 1½", 2½" and 3½" metal cases with ⅛" thick walls, in standard ranges. D.C. moving coil, A.C. moving iron and thermocouple types.

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Triplett

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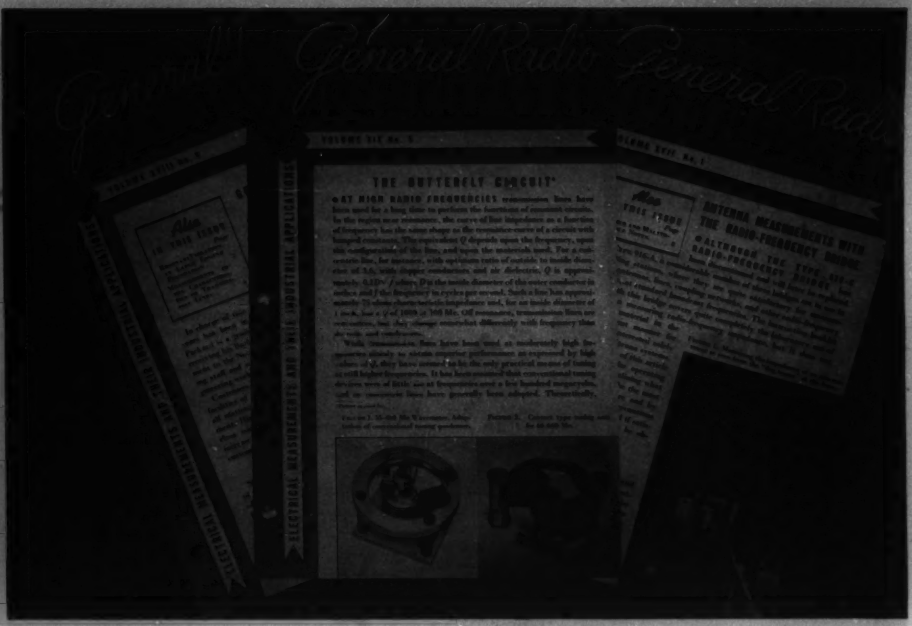

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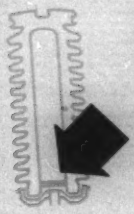
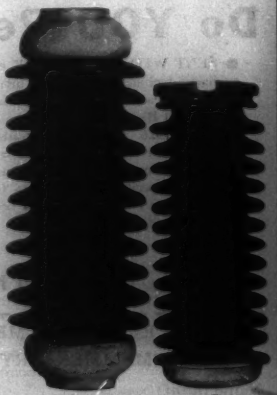
POSITIVE PERMANENT SEAL



Lapp construction of Post insulators—for line and station use—is proved by a 15-year service record, during which Lapp Posts earned a reputation, *on actual record figures*, for most dependable performance under most difficult operating conditions. One reason is found in the exclusive Lapp construction features. Among these is a *porcelain-and-rubber plug*, inserted at the lower end of the finished porcelain, which permanently seals the interior against moisture.

NO HIDDEN CRACKS OR DEFECTS

The Post design is considered difficult of production because of the likelihood of internal cracks near the head of the insulator. Lapp production technique prevents this possibility. Each unit is fired as an open-end post; it is visibly inspected outside *and in*; and full flashover voltage is applied across the head section. This double factor of safety avoids puncture or flashover failure in Lapp Line Posts and Station Posts—assures dependable, economical performance on your system.



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FIRST IN SILICONES

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IN ILLUSTRATION, note regularity of pattern. This is due to uniform shape, density, size, and purity of each particle.

These factors account for high "Q" value—the combination of maximum magnetic permeability and minimum power loss. This is why carbonyl iron powders are better.

The following text gives a brief, complete outline of G.A.F. Carbonyl Iron Powders for those desiring more information.

G.A.F. Carbonyl Iron Powders are obtained by thermal decomposition of iron penta-carbonyl. There are five different grades in production, which are designated as "L," "C," "E," "TH," and "SF" Powder. Each of these five types of iron powder is obtained by special process methods and has its special field of application.

The particles making up the powders "E," "TH," and "SF" are spherical with a characteristic structure of increasingly larger shells. The particles of "L" and "C" are made up of homogenous spheres and agglomerates.

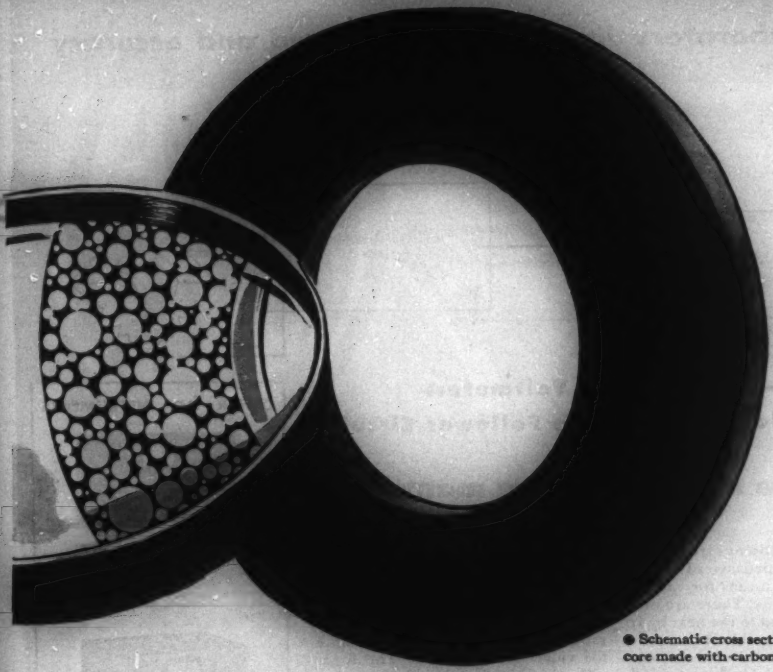
The chemical analysis, the weight-average particle size, the "tap density" and the apparent density are given in the following table for the five different grades:

TABLE 1

Carbonyl Iron Grade	Chemical Analysis % Carbon	% Oxygen	% Nitrogen	Wt. Ave. diameter microns	Tap Density grams/cm³	Apparent Density grams/cm³
L	0.005—0.03	0.1 —0.3	0.005—0.03	30	3.5—4.0	1.8—3.0
C	0.03 —0.12	0.1 —0.3	0.01 —0.1	15	4.4—4.7	2.5—3.0
E	0.65 —0.80	0.45—0.6	0.4 —0.7	5	4.4—4.7	2.5—3.0
TH	0.9 —0.6	0.3 —0.7	0.3 —0.6	3	4.4—4.7	2.5—3.0
SF	0.5 —0.6	0.2 —0.5	0.1 —0.6	3	4.7—4.8	2.5—3.0

With reference to the chemical analysis shown above it should be noted that spectroscopic analysis shows the rest to be iron with other elements present in traces only.

Carbonyl Iron Powders are primarily useful as electromagnetic material over the entire communication frequency spectrum.



● Schematic cross section of powdered iron core made with carbonyl iron powder.

Table 2 below gives relative Q values (quality factors) and effective permeabilities for the different grades of carbonyl iron powder. The values given in the table are derived from measurements on straight cylindrical cores placed in simple solenoidal coils. Although the data were not obtained at optimum conditions, the Q values as expressed in percentage of the best core give an indication of the useful frequency ranges for the different powder grades.

TABLE 2

Carbonyl Iron Grade	Effective Permeability at 1 kc	Relative Quality Factor at 10 kc	150 kc	200 kc	1 Mc	100 Mc
L	4.16	100	96	90	43	1
C	3.45	94	100	98	73	8
E	3.09	81	94	100	97	30
TH	2.97	81	93	98	100	54
SF	2.17	63	71	78	84	100

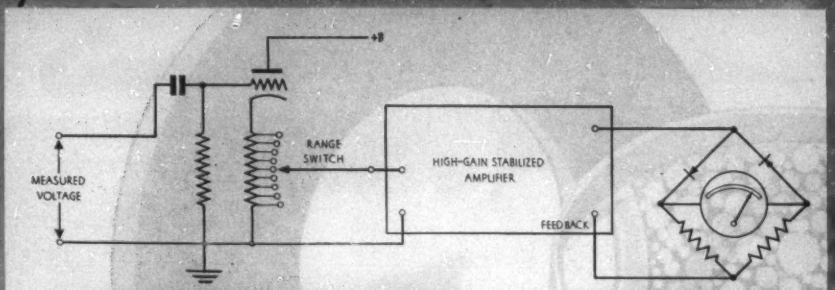
Note: The actually measured Q values can be obtained by multiplying the given percentages with 0.78, 1.05, 1.35, 1.33, and 1.62.)

"L" and "C" powders are also used as powder metallurgical material because of their low sintering temperatures, high tensile strengths and other very desirable qualities. (Sintering begins below 500° C and tensile strengths reach 150,000 psi.)

Further information can be obtained from the Special Products Sales Dept., General Aniline & Film Corporation, 437 Hudson Street, New York 14, N. Y.

G.A.F. CARBONYL IRON POWDERS

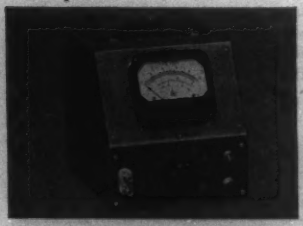
hp laboratory instruments for speed and accuracy



-hp- Vacuum Tube Voltmeters Employ This Cathode Follower Circuit

The advantages are many!

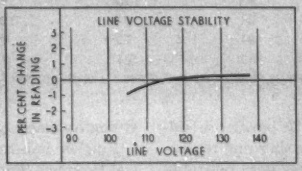
This cathode follower circuit provides an input impedance of 1 megohm and a useful means for varying the meter sensitivity. There are nine ranges, each related to the next by 10 db steps. No adjustment to zero position is required, and the ranges are instantly available by a switch on the panel.



The *-hp-* Model 400A Vacuum Tube Voltmeter consists of the above cathode follower circuit in conjunction with a full wave rectifier and a high gain amplifier. The full wave rectifier actuates a one-mil meter. The amplifier is of the broad band type and is substantially flat from 10 cps to 1 megacycle. Because the amplifier employs inverse feedback, it is extremely stable. Hence the accuracy of meter readings is independent of line voltage and tube characteristics.

Voltages as small as .005 and as high as 300 can be read with positive accuracy and the wide frequency range makes the instrument suitable for video measurements. The logarithmically related scales are also calibrated in db units. Ordinarily no precautions are necessary—wave form errors and "turn-over" effects are minimized—large overload voltages cause saturation of the amplifier which protects the meter.

The *-hp-* Model 400A is designed for the greatest amount of convenience. Its small physical size and large slanting scale make it desirable to use and easy to read. Power supply is completely contained. All-in-all, the *-hp-* Model 400A is probably one of the most useful, versatile instruments in the field. Write for further details.



OTHER -hp- INSTRUMENTS

Noise and Distortion Analyzer

The Model 325B combines a vacuum-tube voltmeter with a set of fundamental elimination filters for general purpose measurements of total harmonic distortion, noise and voltage level.

Electronic Frequency Meter

Model 500A Frequency Meter is designed to measure the frequency of an alternating voltage from 10cps to 50kc.

Audio Signal Generator

The Model 205AG consists of a Hewlett-Packard resistance-tuned oscillator in combination with an input and output meter, attenuator and an impedance matching system.

Secondary Frequency Standard

The Model 100B consists of a crystal controlled oscillator and a series of frequency dividers of the regenerative modulator type to provide standard frequencies of 100 kc, 10 kc, 1 kc and 100 cps.

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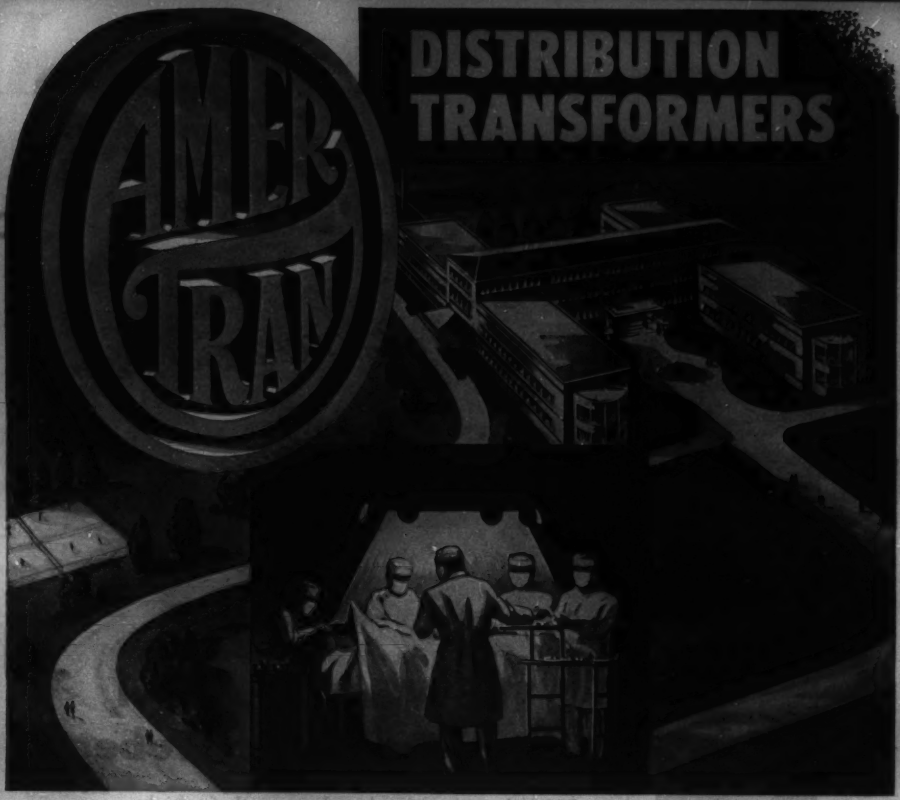

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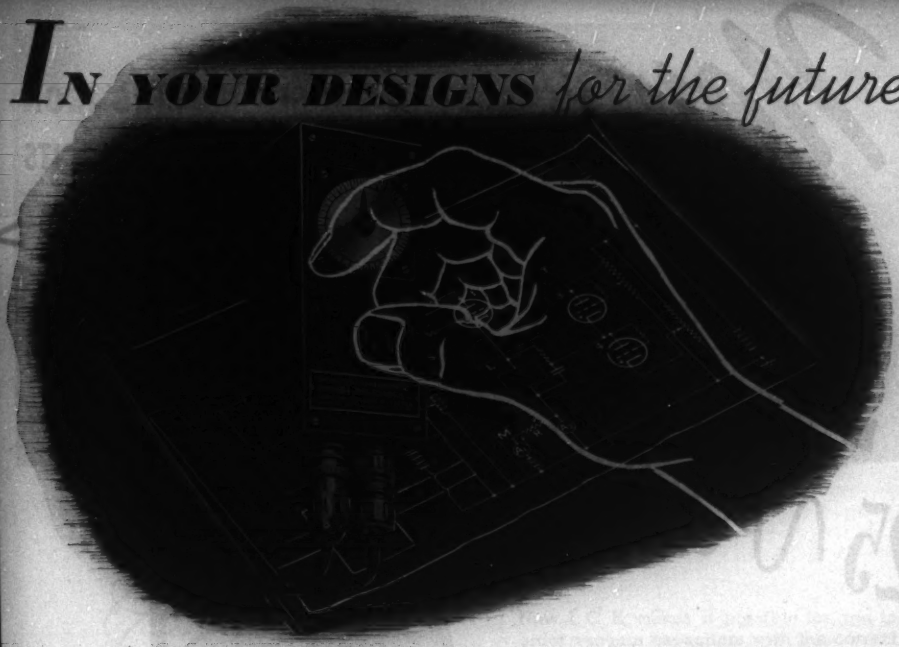

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61 mmfd. to 110 mmfd.	±1.5 mmfd.

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Value Range	*Accurate to*
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26 mmfd. to 60 mmfd.	±0.3 mmfd.
61 mmfd. to 110 mmfd.	±0.5 mmfd.

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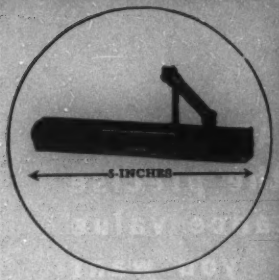

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There is no guessing with a Matthews Teleheight. Any lineman can be taught to use it and get any height within an inch or so. He can learn in five minutes.

The extra cost of just one wrong guess will pay for one or two Matthews Teleheights. Hundreds of them are saving lots of money for their owners all over the country. Many are being used for quickly figuring the cubical contents of buildings, the clearance of bridges, highlines, etc.

Matthews Teleheight is only five inches long. Has no moving parts. It is furnished with a leather carrying case that will fit in the vest pocket. The drawing below shows how simple are the directions for using it.

Great for Appraisal Jobs.

Try one at our risk of your approval.

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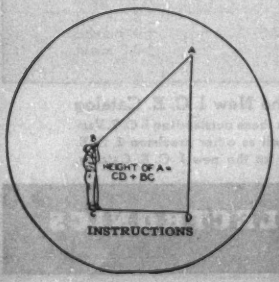

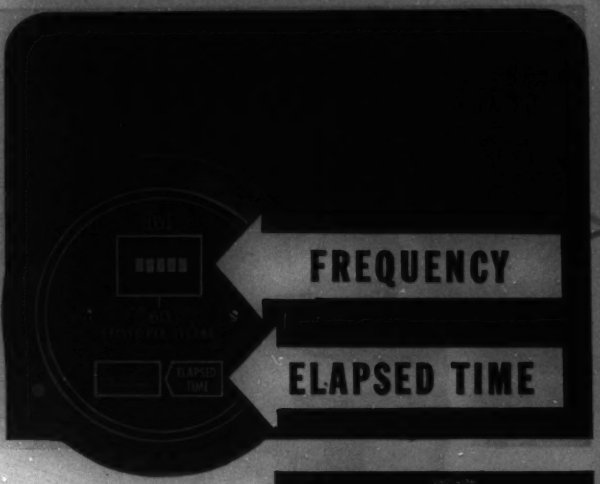

- Saves panel space and weight — one instrument does the work of two
- Insures operation of equipment at proper speed, within ± 0.3%
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Size...3¼" flange diameter. Black metal case for flush-panel mounting. 5 reeds...58-62 cycle range. Accuracy... ± 0.3%. Power consumption... 3 watts, 110 volt operation. Weight...1.3 lbs. Also made for 59-61, 48-52, and 49-51 cycle ranges.

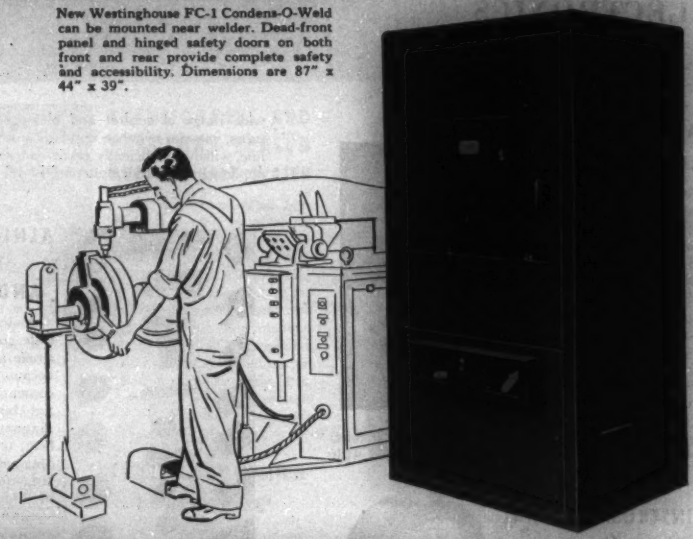
This combination running time and frequency meter is just one of the variations J-B-T has pioneered for specific field and laboratory use in measuring speed, temperature and frequency. This and 17 other interesting applications are illustrated in a new bulletin, now ready.

They may suggest ways to attack your own problems... through use of J-B-T's wide engineering "know how," laboratory set-up and production capacity. Ask for Bulletin VF 43-IC.

P.S. Perhaps you would also like to have Bulletins VF-43 describing basic Vibrating Reed Frequency Meters and their operation, VF 43-IA on 400 cycle meters and VF 43-IB on the smallest frequency meters made. They're yours for the asking too.

S-JBT-4

New Westinghouse FC-1 Condens-O-Weld can be mounted near welder. Dead-front panel and hinged safety doors on both front and rear provide complete safety and accessibility. Dimensions are 87" x 44" x 39".



WHEN YOU WELD ALUMINUM

Production-line aluminum resistance welding with the new Westinghouse electronic Condens-O-Weld capacitor-discharge control brings three big advantages:

1. *faster, more accurate*—speeds up to 200 spots per minute provided by the improved full cycle discharge circuit. Costs are lowered, contactors eliminated.

2. *accurate forging pressure* to assure crack-proof welds. Condens-O-Weld forge timing circuit is the most precise available today.

3. *harmful sparking eliminated* by special Condens-O-Weld circuit design.

Reversing contactors, notching relays and primary shorting contactors are eliminated by Condens-O-Weld design. Maintenance is cut sharply. Operation is speeded and welding current is accurately controlled even though line voltage may vary as much as 20%. Sequence is adaptable to all systems of electrode control for welding both heavy and light gauge aluminum.

You can get complete information about the new FC-1 Condens-O-Weld from your nearest Westinghouse office. Or write Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Penna.

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Single-, dual-, or triple-section units can be supplied for voltages of 600 or 1000 volts, in sizes from 0.05 to 2 microfarads. All units provided with solder-lug "B" terminals. Ask for Bulletin GEA-4357.

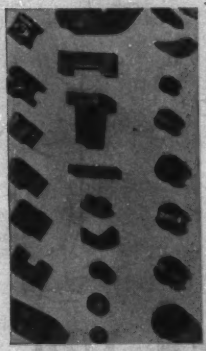
LITTLE INSTRUMENTS THAT CAN "TAKE" A LOT

Internal-pivot construction of G-E small panel instruments makes for compact construction. Accuracy is high, and construction strong. These instruments will withstand momentary overloads of ten times their rated capacity, are resistant to vibration and to temperature, giving accurate reading in the ambient temperature range from −50 C to 70 C. This line (DW-51 and DW-52) includes 15 d-c voltmeters, 10 d-c ammeters, 14 d-c milliammeters, 8 d-c microammeters, 9 r-f ammeters, and 9 r-f milliammeters, all calibrated to cover a wide range of applications in shielded and unshielded types. Send for Bulletin GEA-4064.

INDUSTRIOUS TUBES FOR INDUSTRIAL USES

From the ignitron, supplying hundreds of amperes, to the tiny photo tube that inspects sheet metal at speeds as high as 1000 feet per minute, you'll find G-E tubes putting electronics to work, on all sorts of industrial jobs.

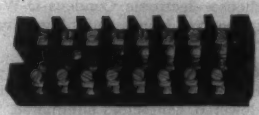
Phanotrons convert a-c to d-c. Kenotrons and ignitrons convert a-c to d-c, and also serve as high-speed circuit interruptors. Thyratrons give "trigger action" or controlled rectification; pliotrons act as amplifiers. Photo tubes are applied to a wide range of control and measurement functions. Ba tubes, vacuum switches, and indicator tubes complete the line, which is sufficiently broad to cover nearly any electr application. Send for Bulletin ETI-12.



ALNICO MAGNETS POWERFUL AND PERMANEN

Alnico magnets make sible compact designs of tronic and electric equipm because of their high en content per unit volume. T are highly resistant to magnetization by vibrat heat, or stray magnetic fi Sintered alnico lends itsel large-quantity production small magnets both simple intricate in shape. Cast al available in five diffe grades, including the h energy alnico 5, is best su for magnets weighing more than 1/10 lb. Ask for Bul GEA-3682B on sintered alnico magnets.

TERMINAL BOARDS FOR EASIER CONTROL WIRING



With G-E Type EB-2 terminal boards, you just strip wire end, and screw the connector down on the bare These solderless pressure connectors will take one No. 8 stranded conductor, two No. 12 stranded, or three No solid conductors. Type EB-1 is the same as EB-2, excep connectors, which are the conventional washer-head type. Both boards are molded from strong, durable Textl both are available in 4-, 6-, 8-, and 12-pole sizes, and come equipped with marking strips. Covers are available

For small wires, a fabricated terminal board (EB-3) is able in sizes ranging from 4 to 38 poles. Send for Bu GEA-1497A.

Timely Highlights on G-E Components

TRANSFORMERS AND REACTORS SEALED AGAINST SALT WATER

G-E compound-filled hermetically sealed transformers and reactors are built to withstand the rigorous salt-water immersion and salt-spray tests, as specified by the Signal Corps, Air Forces, and Navy. This hermetic sealing also keeps out dust, dirt, and micro-organisms. The line includes transformers for plate and filament supply; also microphone, input, interstage (or grid), and modulation transformers and output units for the audio-frequency range. Reactors are included for filter, modulation, microphone, and plate circuits. Standard hermetic cases vary from approximately two cubic inches to 150 cubic inches in volume. Send for Bulletin GEA-4280.

RESISTORS IN WHICH I VARIES AS E⁴

In Thyrite*, G.E.'s nonlinear, silicon-carbide resistance material, current varies as a power of the applied voltage (I varies as E^n). Doubling the voltage in a wire-wound resistor doubles the current. Doubling voltage in Thyrite increases the current 16 times, where the exponent (n) of the Thyrite is 4. Because of this characteristic, Thyrite has solved many problems in electronic circuits, by protecting them against voltage surges, stabilizing power voltages, controlling voltage-selective circuits, etc. Thyrite is usually supplied in disk or rod form, in diameters ranging from 0.25 in. to 6.00 in. Send for Bulletin GEA-4138A.

A LITTLE SWITCH FOR BIG JOBS

The G-E Switchette weighs less than one-third of an ounce; its case measures only ½ by 21/32 by 1¼ inches, yet it is rated 230 volts; 10 amperes a-c.

Low-inertia moving parts, and high, contact pressure assure fast, positive action even where vibration is severe. The spring-return button can be actuated manually, or by cam or bellows. Switchettes are available in three general-purpose double-break contact arrangements with terminals on top or at ends. Switchettes are designed to meet the 50-hour Government salt-spray test, and operate from sea level to 50,000 feet altitude. Bulletin GEA-3818A describes more than 100 types and arrangements.

*Trade-mark reg. U.S. Pat. Off.

Capacitors • Sensitive control and time-delay relays • Limit switches • Motors, dynamotors, amplidynes • Motor-generator sets • Alnico magnets • Small panel instruments • Formex* magnet wire • Radio transformers • Switchettes • Selsyns • Chokes • *also tubes, crystals, plastics products, insulation materials, and many others*

General Electric Company, Sec. 642-7
Schenectady 5, N.Y.
Please send me

.....GEA-4357	.....GEA-1497A
.....GEA-4064	.....GEA-4280
.....ETI-12	.....GEA-4138A
.....GEA-3682B	.....GEA-3818A

NAME .....
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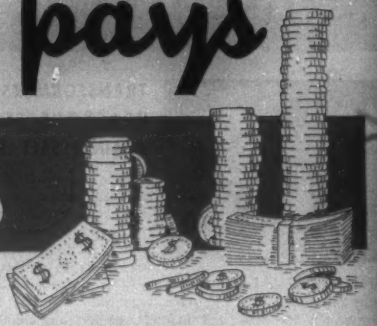
2010

Research pays Dividends



When the war came along and we were deprived of our supply of deproteinized rubber we all thought, "Well, that's the end of ANHYDREX until after the war." However, our very capable technical staff came through with an ANHYDREX Buna rubber insulation that we are proud to offer.

This new insulation has a water absorption rate of only .020 grams per square inch of exposed surface. Add to this freedom from electrolysis, installation with or without ducts and you have a combination that's pretty hard to beat.

If you have underground power, control or submarine cable problems that are bothering you, tell your Simplex Engineer about them. He will be more than glad to help you at no obligation whatsoever and you will be assured of getting the latest and most modern engineering advice on your problem.

Simplex Wire & Cable Co., 79 Sidney Street, Cambridge 39, Mass.

Simplex
WIRES and CABLES

JOINED...FOR LIFE *through Corning Metallizing!*

REMEMBER when glass and metal just wouldn't stay hitched? They joined together readily but when the going got rough they parted company in the best Hollywood tradition.

Things are different now. *Corning's* metallizing process weds glass and metal with a bond that lasts like an old-fashioned marriage. Through heat and cold . . . under severe conditions of stress and strain, they stick together in a lasting union.

This happy union can boast a whole family of fine qualities:

HERMETIC SEALING . . . PRECISION METALLIZING . . . SUPERIOR PHYSICAL PROPERTIES . . . PERMANENCE . . . THERMAL ENDURANCE . . . MECHANICAL STRENGTH

Which of these can you use? Write us about it. We'll be glad to work with you to see if metallized glass can help solve your problem. Address Electronic Sales Department, N-6, Bulb and Tubing Division, Corning Glass Works, Corning, New York.

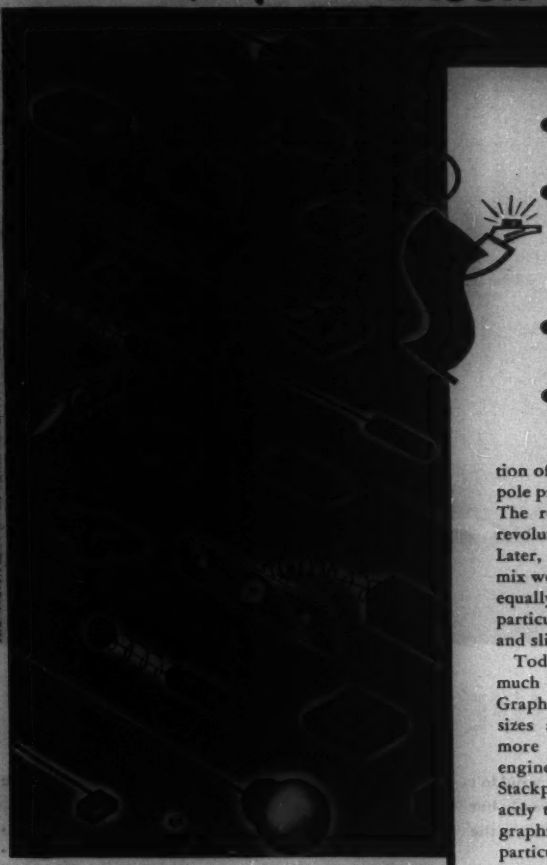
CORNING *means* Research in Glass

Electronic Glassware

VYCOR CORNING PYREX

"PYREX", "VYCOR" and "CORNING" are registered trade-marks and indicate manufacture by Corning Glass Works, Corning, N. Y.

Silver-Graphite BRUSH HEADQUARTERS



- **LESS RADIO INTERFERENCE**
- **LESS AUDIO AND RADIO FREQUENCY NOISE**
- **LOW CONTACT RESISTANCE**
- **UNIFORM CONTACT RESISTANCE**
- **LONG LIFE**

Twenty years ago, at the suggestion of Westinghouse engineers, Stackpole pioneered silver-graphite contacts. The result was an almost immediate revolution in circuit breaker design. Later, as the advantages of this unique mix were applied to brush engineering, equally important advances were scored, particularly on low-voltage commutator and slip ring motor applications.

Today, the important thing is not so much the fact that Stackpole Silver-Graphite Brushes are supplied in all sizes and shapes. What counts even more is the unsurpassed wealth of engineering experience that permits Stackpole engineers to recommend exactly the correct, "tailor-made" silver-graphite mix for best results on your particular application. Backed with complete details of your equipment, they welcome the opportunity to submit Silver-Graphite Brush (or Contact) samples for test. You be the judge!

STACKPOLE CARBON COMPANY
ST. MARYS, PA.

BRUSHES AND CONTACTS
(All carbon, graphite, metal, and composition types)
RARE METAL CONTACTS
BEARINGS **WELDING CARBONS**
PACKING, PISTON AND SEAL RINGS
CONTINUOUSLY ADJUSTABLE CARBON RHEOSTATS
CHEMICAL CARBONS
CARBON PIPE **POWER TUBE ANODES**
MOLDED SPECIALTIES, etc.

STACKPOLE
MOLDED METAL POWDER AND CARBON PRODUCTS

NO. 4 IN THE IRC NEW PRODUCT PARADE

Seaworthy!... and IRC-Worthy

GRADE 1 — CLASS 1 RESISTORS

Exhaustively tested for dependable performance and sound construction, IRC's Type GRW *GRADE 1—CLASS 1 RESISTORS* are now available. Only after every requirement of Army-Navy specification Jan-R-26 had been met or surpassed would our Engineering Department approve this product for the applications for which it is designed.

Resistant to salt water immersion following thermal shock, they are capable of continuous efficient operation at a total temperature of 275° C. (ambient plus rise).

Made in 7 standard sizes with power ratings from 15 to 140 watts and resistance ranges of from 0.1 to 63000 ohms, the GRW's are enclosed in special heat-treated glass for optimum strength. Non-corrosive ferrules are hermetically sealed to the tube with pure lead. Nickel alloy leads pass through the centering devices and are welded to the outer ferrule cups. All resistors are *space wound*.

These IRC GRADE 1—CLASS 1's are engineered to "take it" far beyond normal requirements and can stand transverse loads as high as 100 pounds without failure or damage of any kind.

IRC — INSURES THE PERFORMANCE OF YOUR APPARATUS — RESISTORS

Write today for special Engineering Bulletin containing dimension drawings, temperature rise and de-rating curves as well as other technical data.

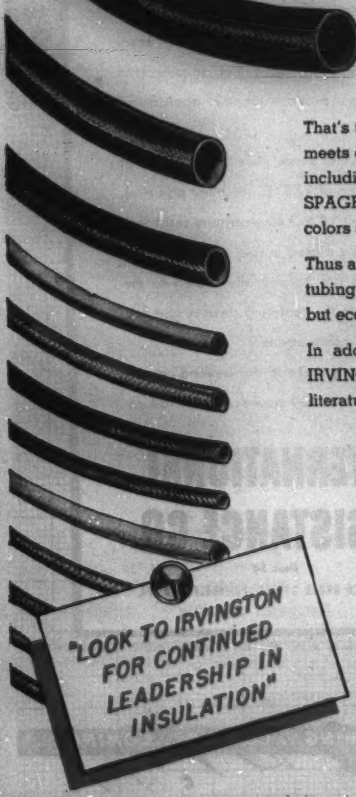
INTERNATIONAL RESISTANCE CO.

Dept. 5-F

401 NORTH BROAD STREET, PHILADELPHIA 8, PA.

ARE YOU USING THE TUBING *best* SUITED FOR YOUR JOB?

Irvington *can Supply it*



BEST suited means a varnished tubing or sleeving that meets *every* service requirement . . . at *lowest cost!*

That's the way IRVINGTON . . . long the leader in electrical insulation . . . meets *every* tubing or sleeving need. For IRVINGTON makes *all* the types including non-fraying FIBERGLAS . . . high voltage IRV-O-VOLT . . . RADIO SPAGHETTI and SATURATED SLEEVINGS . . . in a complete range of colors and A. S. T. M. sizes.

Thus a recommendation from IRVINGTON can be unbiased . . . you get the tubing *best* suited to your needs. not only from the standpoint of efficiency, but economy as well.

In addition, you get that extra increment of electrical surety which IRVINGTON'S 'know how' and 'manufacturing control' provides. For literature, or engineering assistance, write to Dept. 36.

IRVINGTON PRODUCTS:

Cotton, Fiberglas, or Rayon Tubings and Sleevings — Varnished, Lacquered, or Vinylite Processed

Non-Fraying Fiberglas Sleeving

Transformer Lead Tubings

Wire Identification Markers—Varnished or Plastic

Extruded Plastic Tubings

Fibron Plastic Tapes

Varnished Fabrics and Papers

Slot Insulations

Harvel and Irvington Insulating Varnishes

Cardolite Resins

IRVINGTON
VARNISH & INSULATOR COMPANY
Irvington 11, New Jersey

A NEW MINIATURE TUBE—
THE RCA-OA2

Actual Size

Now RCA Miniature Voltage-Regulator Tube Operates at 150 Volts—Is Practically Equivalent to Standard 0D3/VR150

FOR the first time, equipment designers have available in a miniature envelope a voltage-regulator tube capable of performing the functions previously requiring a standard-size tube. This space-saving feature is especially valuable where compact military equipment is being designed. The OA2 will provide as many hours of service as standard-size tubes.

Like standard-size voltage-regulator tubes, the OA2 is a cold-cathode, glow-discharge tube. It is intended for use as a voltage regulator in applications where it is necessary to maintain a constant d-c output voltage across a load, independent of load-current and moderate line-voltage variations.

The OA2, like other voltage-regulator tubes, can also be used for spark-over protection.

For information on this and other RCA Electron Tubes, mail the coupon or write to RCA, Commercial Engineering Section, Dept. 62-32A, Harrison, N. J.

TECHNICAL DATA

Maximum Overall Length, Inches	2⅛
Maximum Seated Height, Inches	2⅛
Maximum Diameter, Inches	¼
Bulb	T-5½
Base—Miniature Button, 7-Pin	Mounting Position—Any
D-C Anode Supply Voltage, Minimum, Volts*	185
D-C Operating Current	
Continuous Maximum, Milliamperes	30
Continuous Minimum, Milliamperes	5
Ambient Temperature Range, Degrees C	—55 to +90
D-C Starting Voltage, Approx. Volts	155
D-C Operating Voltage, Approx. Volts	150
Regulation (5 to 30 Milliamperes), Volts	2

*Not less than indicated supply voltage should be provided to insure "starting" throughout tube life.

The Fountainhead of Modern Tube Development is RCA

MAIL THIS TODAY FOR FREE DATA SHEET

RCA, Commercial Engineering Section, Dept. 62-32A, Harrison, New Jersey.

Please send data sheet on RCA's new miniature voltage-regulator tube, the OA2, giving ratings, operating and installation notes, terminal connections, and typical circuits.

Name .....

Position .....

Company .....

Address .....

City ..... Zone ..... State .....

RCA

RADIO CORPORATION OF AMERICA

RCA VICTOR DIVISION · CAMDEN, N. J.

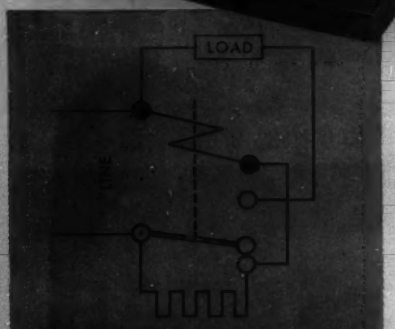
Sensitive SNAP-ACTION

...in a new, simplified design

The new, simplified construction of the Struthers-Dunn Type 79XAX Sensitive Snap-Action Relay makes it particularly suitable for a wide range of applications because of its ease of adjustment. Snap-action design assures full normally-closed and normally-open contact pressures. Erratic operations and varying contact resistance encountered with ordinary sensitive relays, due to slowly changing coil flux balancing armature spring tension, are eliminated.

The armature of the 79XAX almost completes its travel in either direction before the contacts snap into the new position. This feature permits an unusually broad range of use from vacuum tube circuits, to overcurrent protection, pulsing circuits, and jobs where extremely close differential or extreme sensitivity of operation is required.

The standard adjustment using 60 ampere turns in the coil at approximately .02 watts results in contact pressures of 5 grams with contacts rated 5 amperes, 115 volts a-c; or 0.5 amperes, 115 volts d-c, non-inductive. Contact ratings up to 10 amperes, 115 volts a-c may be obtained with 100 or more ampere turns and a corresponding increase in power. A sensitivity of 0.005 watts, with 30 ampere turns, is obtainable with reduced contact pressures and ratings, and at an increase in price of the unit.



A TYPICAL CLOSE DIFFERENTIAL APPLICATION

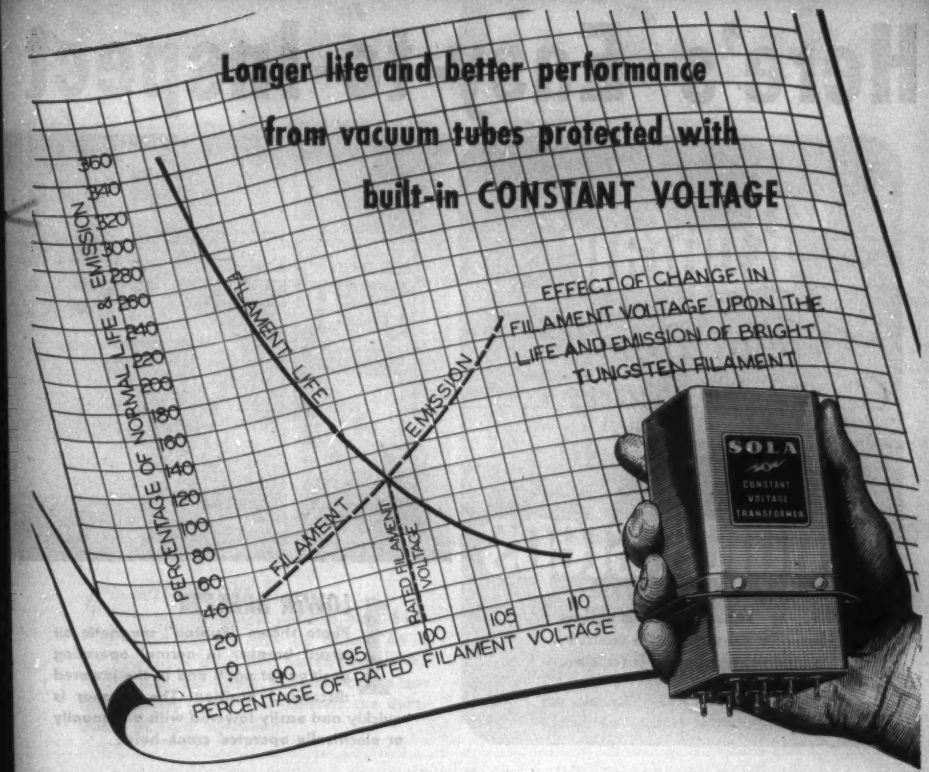
In using the Struthers-Dunn 79XAX relay, extremely close differential between pick-up and drop-out may be obtained for potential operation as shown above. The resistor is chosen so that, when the armature closes, the coil current is automatically reduced to a value just sufficient to hold it closed. Any further decrease in voltage will cause the relay to return to its normal de-energized position and engage

STRUTHERS-DUNN INCORPORATED
1321 ARCH STREET, PHILADELPHIA 7, PA.

STRUTHERS-DUNN

ATLANTA · BALTIMORE · BOSTON · BUFFALO · CHICAGO · CINCINNATI · CLEVELAND
DENVER · DETROIT · HARTFORD · INDIANAPOLIS · LOS ANGELES · MINNEAPOLIS · MONTREAL
PITTSBURGH · ST. LOUIS · SAN FRANCISCO · SEATTLE · SYRACUSE · TORONTO · WASHINGTON

Longer life and better performance from vacuum tubes protected with built-in CONSTANT VOLTAGE



A 5% over-voltage will reduce the life of a tungsten filament by 50%.

A 5% under-voltage will cut filament emission by 33%.

Commercial line voltages today may vary as much as ± 20%.

With a SOLA Constant Voltage Transformer as a built-in component of your equipment, these line voltage variations can be ignored. No need to depend upon operator adjustments. No need to worry about operator forgetfulness. You can depend on it—the right voltage is *always* there.

Vacuum tubes protected by SOLA Constant Voltage Filament Transformers require no starting resistors or high reactance transformers. Filaments are automatically and positively protected against damaging inrush currents. Tube life is noticeably prolonged.

SOLA Constant Voltage Transformers require no supervision, or manual adjustments by the operator. They eliminate the need for voltmeters. They are fully automatic, have no moving parts, tubes or networks, and are self-protecting against short circuit.

Standard units are available in capacities from 10 VA to 15 KVA either for the operation of equipment now in use or as built-in units. Where special problems confront the designer, consultation with SOLA engineers may provide a positive and economical solution.

SOLA Constant Voltage Transformers

To Manufacturers:
Built-in voltage control guarantees the voltage called for on your label. Consult our engineers on details of design specifications.
Ask for Bulletin ACV-102

Transformers for: Constant Voltage • Cold Cathode Lighting • Mercury Lamps • Series Lighting • Fluorescent Lighting • X-Ray Equipment • Luminous Tube Signs Oil Burner Ignition • Radio • Power • Controls • Signal Systems • Door Bells • and Chimes • etc. **SOLA ELECTRIC CO., 2525 Clybourn Ave., Chicago 14, Ill.**

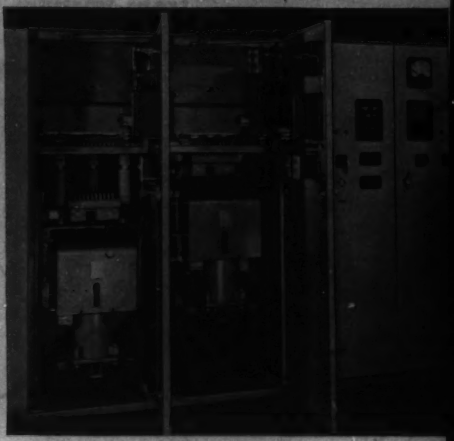
Here's Easy-to-Inspect

"Ruptair"

Circuit Breaker Contacts Ready for Inspection in

3 quick steps

NOTE: Inherently, this oilless breaker requires little maintenance . . . inspection is routine.



1 LOWER BREAKER

Photo shows "Ruptair" magnetic air circuit breaker in normal operating position (at right) and in the lowered disconnect position. The breaker is quickly and easily lowered with a manually or electrically operated crank-hoist.

FOR MODERATE capacity installations, 5 kv and below, the "Ruptair" magnetic air breaker is increasingly popular among operators. Because oil is eliminated from the breaker, fire hazard is reduced, and maintenance requirements are much less . . . particularly for repetitive operation.

In addition to these advantages, and simplest inspection of any magnetic air breaker, the "Ruptair" breaker combines vertical lift construction with horizontal contact separation, illustrated on opposite page.

"Ruptair" breakers are built in standard ratings of 5 kv, 150,000 kva capacity and below.

ALLIS-CHALMERS LETS THE CUSTOMER "HAVE HIS SAY"

You Can Choose From 3 Basic Types of Circuit Breakers

☛Allis-Chalmers wholeheartedly endorses the principle of standardization, wherever the interests of customers are best served. Actually, A-C *introduced* standard metalclad switchgear units to U. S. industry.

☛What Allis-Chalmers has *not* yet done is to limit *types* of circuit interrupters available in switchgear units. For our A-C engineers believe that the customer rightfully plays an essential part in the development of industrial equipment.

☛Take military aircraft as a parallel case to switchgear. A problem never really solved by the "efficient" German Luftwaffe—that of preparing planes for combat under current combat conditions — was licked by the U. S. Air Forces in a typically American way after Pearl Harbor, when pilot (customer) experience was utilized at Aircraft Modification Centers.

☛In the same way, by offering oil, magnetic air, and air blast breakers for buyer choice, A-C lets the customer "call his own tune" . . . cooperate in the *evolution* of tomorrow's circuit breaker.

Magnetic Air Breaker

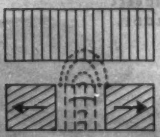
2 WITHDRAW IT

In the disconnect position, the "Ruptair" breaker can be placed on a transfer truck, and pulled out into the aisle. For safety, shutters used to isolate primary disconnect contacts are automatic in their operation.

3 REMOVE SIDE PLATES

Finally, light-weight insulating barriers are removed, each barrier being held in place by two cap-screws. Since the "Ruptair" arc chute is above the contact structure, it need not be disturbed for contact inspection.

"Ruptair" Circuit Breaker is Engineered For Maximum Interrupting Efficiency

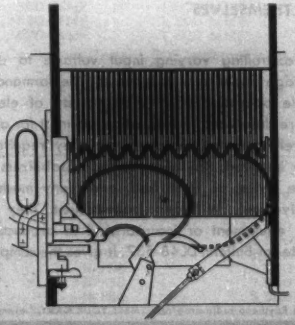


THE "RUPTAIR" breaker depends for efficiency over entire interrupting current range on several design factors . . . one of which is horizontal contact separation.

Since arcing contacts part in the horizontal direction, the arc is assisted into the arc chute by natural thermal effect — no complex interrupting structure is required! In addition, position of arc chute *above* contacts makes it possible to inspect the contacts without removing the chute.

By the coordination of contacts and arc runners, shown in the accompanying diagram, the arc is quickly and easily transferred from the horn-shaped moving contact to the stationary arc runner, opposite.

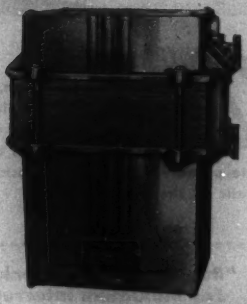
Another unique feature is the intermediate stationary contact which fully connects the magnetic blowout coil into the circuit before actual contact separation . . . results in augmented blowout effect.



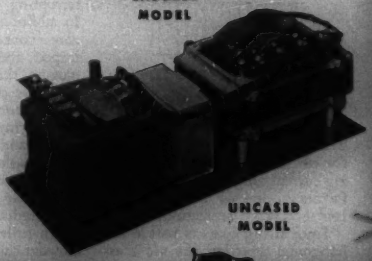
ALLIS CHALMERS

RAYTHEON VOLTAGE STABILIZERS

CASED MODEL



ENDBELL MODEL



UNCASED MODEL

- STABILIZE VARYING LINE VOLTAGES TO ±½%
- STABILIZE WITHIN 2 CYCLES
- STABILIZE VOLTAGES FROM 95 TO 130 VOLTS OR 190 TO 260 VOLTS
- ARE FULLY AUTOMATIC IN OPERATION
- SIMPLY CONNECT THEM . . . AND THEY'LL TAKE CARE OF THEMSELVES

By controlling varying input voltage to ±½%, Raytheon Voltage Stabilizers improve the performance and assure reliable operation of a wide variety of electrical equipment where close voltage regulation is a must for accurate operation. Entirely automatic in operation, they require no maintenance once installed. Raytheon Voltage Stabilizers are available in three styles, as illustrated, and many models to meet practically every installation requirement. They can be built into new equipment or incorporated in products already in use. Write for Bulletin DL48-537. It gives the complete story.

Tune in the Raytheon radio program: "MEET YOUR NAVY," every Saturday night on the Blue Network. Consult your local newspaper for time and station

RAYTHEON MANUFACTURING COMPANY
Electron Equipment Division
190 WILLOW STREET WALTHAM, MASS

The coveted Army-Navy "E," for Excellence in the manufacture of war equipment and tubes, flies over all four Raytheon Plants where over 16,000 men and women are producing for VICTORY.

Devoted to research and manufacture of complete electronic equipment; receiving, transmitting and hearing aid tubes; transformers; and voltage stabilizers.

ERIE HIGH VOLTAGE CERAMICONS*

Set New Standards of Operating Efficiency

ERIE Ceramicon Designs for high voltage, high current applications have proven ideal because the ceramic dielectric with silvered electrodes provide extreme stability and temperature compensation, permitting operation at elevated temperatures. Due to the high capacity per dielectric and rigidity of plates, inner connections are simplified, circulating currents minimized and operation at high frequencies made more efficient.

Corona shields are designed directly into the ceramic dielectrics which are fabricated in the most desirable shape for this purpose. Erie Ceramicon Designs are simplified and better adapted to high frequency use because a single plate can be provided with integral corona shields, for the total voltage. This makes series connections for multiple plate condensers unnecessary. These features are incorporated in all Erie high voltage, high current Ceramicons.

Typical characteristics of the two types illustrated above are shown in table below. Send us your specific requirements. Complete information will be sent promptly without obligation.

CHARACTERISTICS

680 A

Standard Capacities

NPO	N-750
120 MMF	330 MMF
240 MMF	680 MMF
360 MMF	1,000 MMF
510 MMF	1,300 MMF
620 MMF	1,800 MMF

Max. Safe Continuous Current, 30°C ambient at sea level.

Capacity MMF	Amps. @ 1Mc	Amps. @ 3Mc	Amps. @ 20Mc
330	5	7	10
1,800	12	15	20

Test voltage 6000 volts RMS, 60 CPS, 10,000 volts D. C.

741 A

Capacity	Temperature Coefficient	Peak Working Volts at Sea Level
20 MMF	NPO	10,000
30 MMF	NPO	6,500
39 MMF	NPO	5,000
51 MMF	N-750	10,000
75 MMF	N-750	7,500
100 MMF	N-750	5,500

*Ceramicon is the registered trade name of silvered ceramic condensers made by Erie Resistor Corporation.

Electronics Division

ERIE RESISTOR CORP., ERIE, PA.

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FOR HIGH ACHIEVEMENT IN WAR PRODUCTION

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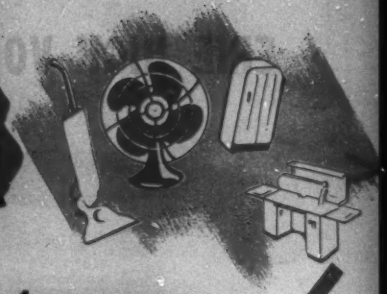

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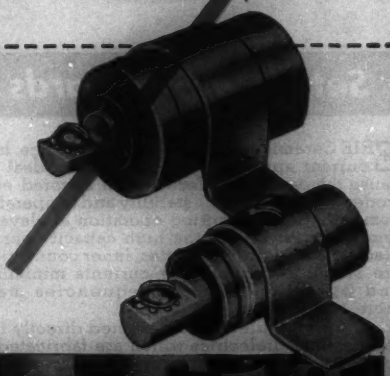

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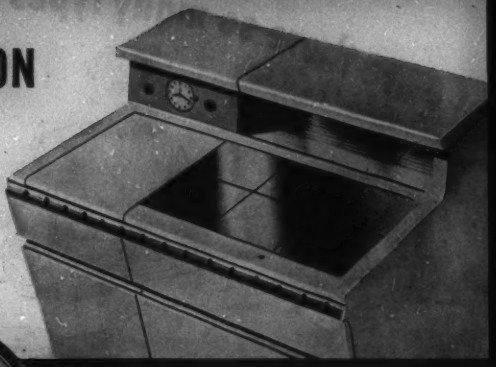

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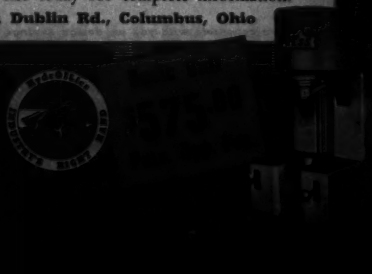

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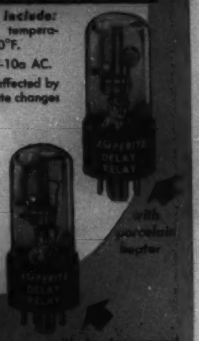

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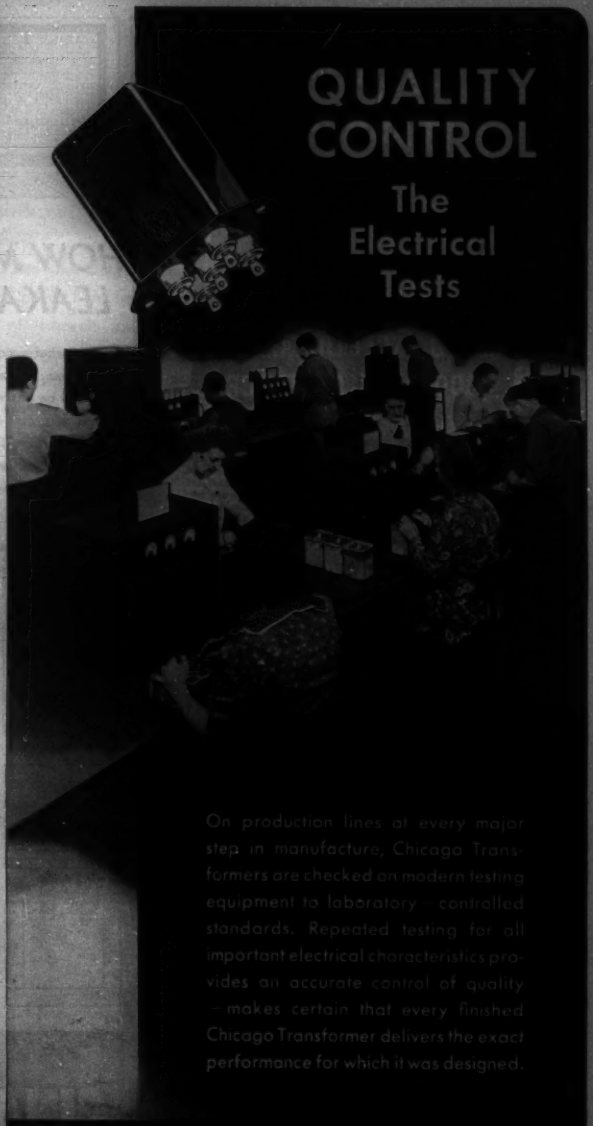
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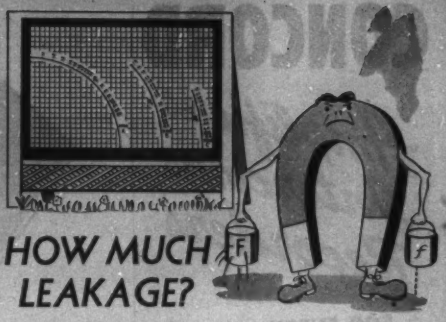

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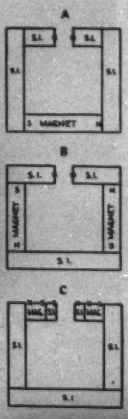

With values for Constants F and f determined, the energy equation can be solved. Full details are given in our booklet, PERMANENT MAGNET DESIGN. Send for a copy. Study it and if you would like any assistance in designing your magnets, call on us.

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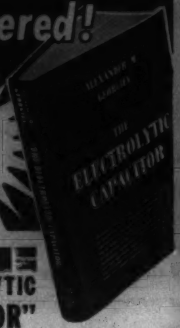

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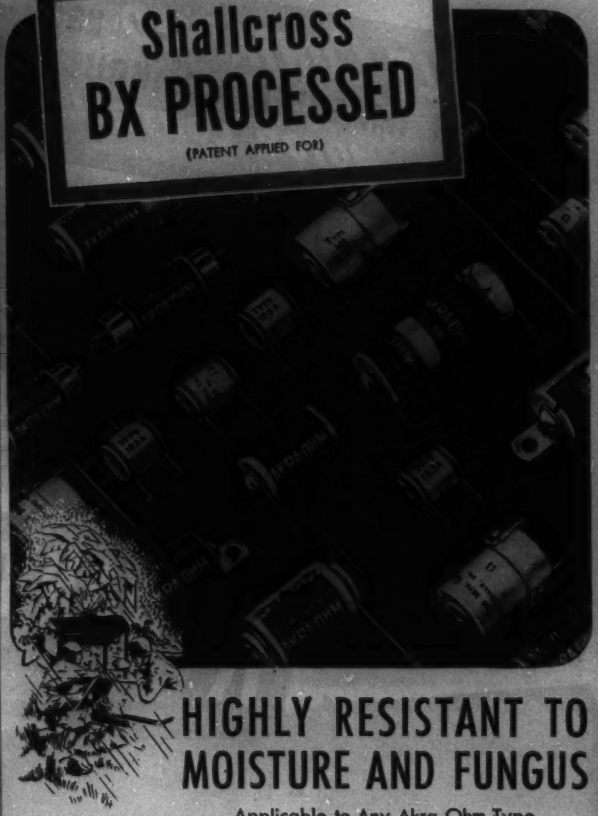

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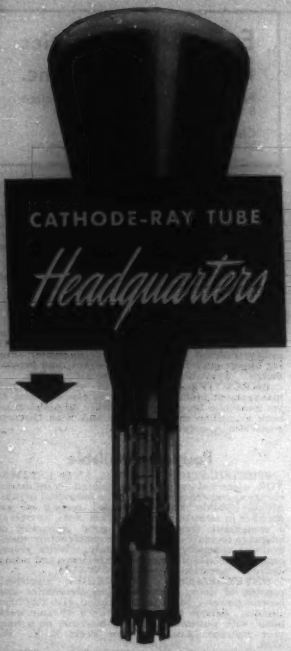

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SPECIFICATION WRITER AND ESTIMATOR, electrical engineer, experienced on industrial electrical construction for a large industrial organization. Should have successful record of experience in estimating construction costs, as well as a competent viewpoint and good command of language to enable him to write construction specifications concisely and accurately. Write giving complete details of education, experience and salary desired. Location, Michigan. W-5144.

DEVELOPMENT ENGINEERS, electrical, capable of doing some work in electronics and general power. Must be acquainted with amplifier circuits. Salary, $3900 a year on a 48-hour week basis, with possibility of 15% increase, on a one-year contract. Location, New York, N. Y. W-5295.

ELECTRICAL OR MECHANICAL ENGINEER, graduate, to make studies and reports on technical phases of department including heating, power and water facilities in large ordnance plant. On-the-job training with expectation of becoming assistant to Utilities Superintendent. Salary, 2700–$3900 a year. Location, western Tennessee. W-5277(b).

CHIEF ENGINEER, 40–45, electrical graduate or equivalent, with considerable administrative, process and development experience in high frequency cable work. Salary, $6000–$7200 a year. Location, New Jersey. W-5294.

MECHANICAL OR ELECTRICAL ENGINEER for a large electrical and mechanical manufacturer for work in new products division. Requires familiarity with engineering, manufacturing, sales and management problems. Ability to make engineering and commercial surveys. Salary open. Location, Pennsylvania. W-5303.

CHIEF DRAFTSMAN with electrical instrument and some electronic experience. Salary, $3640 a year. Location, Connecticut. W-5316(a).

ELECTRICAL DEVELOPMENT ENGINEER experienced in the high frequency field in connection with making new chemical processes in which high frequency current is important. Salary, $4000–$6000 a year. Location, New York State. W-5320.

ADVERTISING ENGINEER, electrical, with sufficient knowledge of engineering principles to understand transforming and with some experience in advertising. Will take charge of advertising appropriation, creation of trade paper advertising, sales literature, engineering manuals, etc. Salary, about $5200 a year. Location, northern New Jersey. W-5350.

FIELD ENGINEER, 30–45, electrical, or mechanical with electrical experience, to supervise, install and maintain radio and radar equipment. Considerable traveling involved. Salary, $4000–$5000 a year, plus traveling expenses. Headquarters, New York, N. Y. W-5354.

ELECTRICAL ENGINEER, 28–42, graduate of a recognized engineering school and having an M.S. degree, for position of Professor and Chairman of Electrical Engineering Department. Teaching experience is essential and experience in research, investigation and/or development as well as authorship of published articles, bulletins and texts are important considerations. Salary, $2800 on a nine-month basis. Location, North Dakota. W-5374.

DESIGNERS AND DETAILERS. (a) Senior Tool Designers with experience on small jigs and fixtures. (b) Experienced Detailers on tools, dies, as well as jigs and fixtures. Postwar opportunities. Organization manufacturing electric motors. D-2286.

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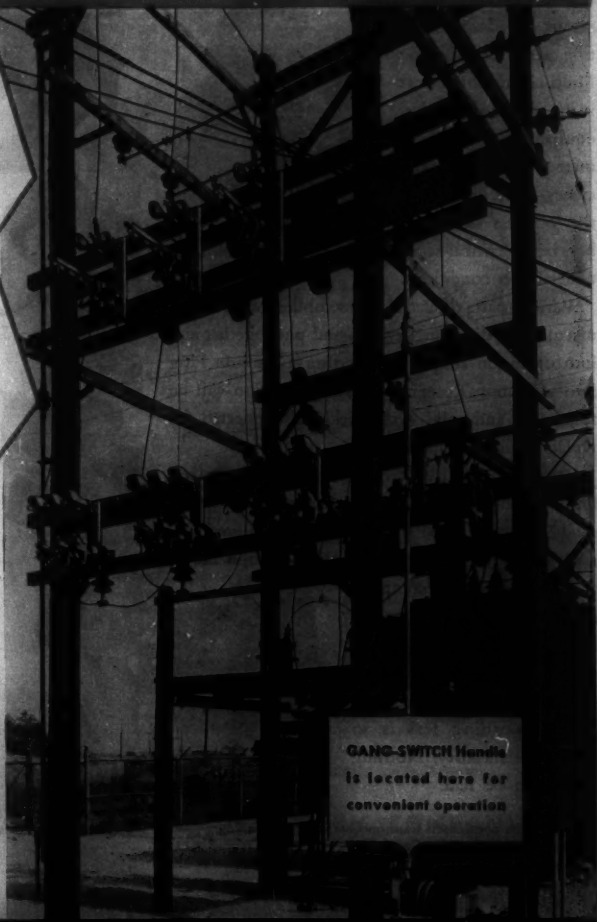

Applications like the one on this transformer substation, are gaining ever-growing acceptance . . . because they simplify installation . . . and give safe, dependable load-switching and short-circuit protection at worthwhile savings. It will pay you to write for Bulletins 202A and 215.

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Bench assembly and repair means speed-up in production. The use of Cannon Multi-circuit Connectors in the wiring of electrical equipment is the ultimate in assembly efficiency—time saved on the job, less skilled labor, better critical work under better conditions.

Bench wiring by Joan Wheeling of the Curtiss-Wright Corporation, Columbus, Ohio

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Write for the condensed Cannon Catalog. It gives you a general introduction to the Cannon line. Address Dept. A-311, Cannon Electric Development Company, 3209 Humboldt St., Los Angeles 31, California... ***Below is pictured a wall mounting, typical of the famous Cannon AN line of plugs.***

CANNON ELECTRIC

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. . But you can see the results

Pieced together this picture shows one step in the making of dials for Simpson Instruments. We have scrambled it deliberately to emphasize the fact that Simpson employs many processes others do not in manufacturing electrical instruments and testing equipment. To the man who knows instruments this extra measure of engineering skill and craftsmanship is evident in every detail—a reflection of Simpson's never-ending quest for refinements in design that will at once improve performance and permit more efficient production. It is the experience gained through more than 35 years of such study which promises you, in Simpson Instruments, the ablest application of the great advances that will be forthcoming.

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Sprague *CEROC 200 is an inorganic wire insulation having outstanding space factor and high-temperature advantages:

- *Applied to copper, nickel, or other types of wire, it permits continuous operation at 200°C.*
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Sprague *CEROC 200 is by no means a new or untried development. Pioneered and perfected by Sprague several years ago, it has been supplied exclusively and in large quantities for war applications. Its *proved* advantages are these:

Wire insulated with *CEROC 200 can normally be supplied in sizes to meet almost any coil, transformer, or motor need. Although practically 100% of the present greatly expanded production is still going for war uses, samples of several popular sizes are available in "engineering" quantities. These represent a real opportunity to those who recognize the tremendous design advantages inherent in this unique insulation development, and who seek to test it, not so much for existing products but in relation to entirely new or re-designed products that look to the future.

*Write today for copy of *CEROC 200 Bulletin 505*

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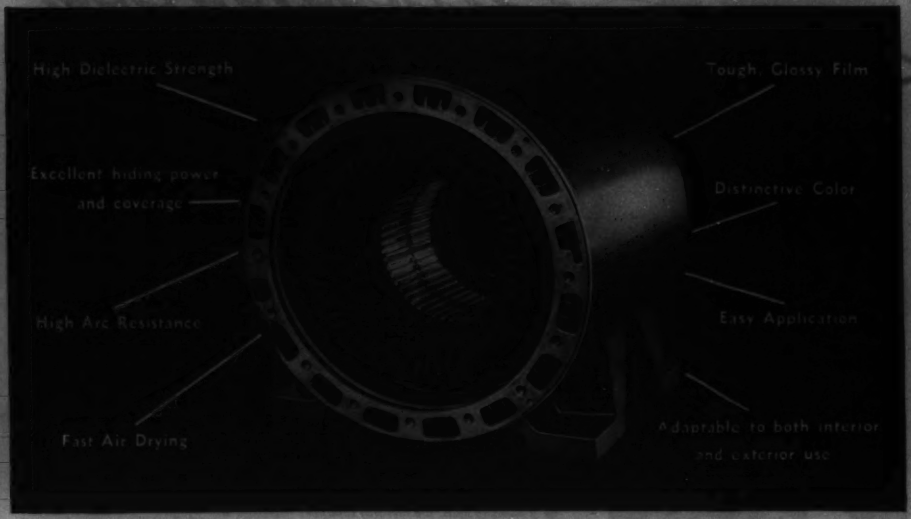
Protection DOLPH'S #10 RED INSULATOR



Illustration—Stator of Continental Electric Explosion-proof Motor

"WET DIELECTRIC UNCHANGED AFTER 3500 HOURS OF HEAT-AGING AT 275°F."

Yes, *SYNTHITE #10 Red Insulator was actually subjected to this severe test and passed it with "flying colors." SYNTHITE #10 Red Insulator was applied over two coats of clear baking varnish on a brass surface, and HEAT-AGED FOR 3500 HOURS AT 275°F. After this period, the test specimens were immersed in distilled water for 24 hours. The wet dielectric strength of the varnish after this treatment did not vary materially from the wet dielectric determined before the test, and the varnish film was in good condition.

Applied by brush or spraying over prevarnished surfaces, SYNTHITE #10 Red Insulator affords maximum protection against chemical fumes, oil, water, acids and alkalies. In fact, the chemical resistance of SYNTHITE #10 is so great that engineering departments of various industries such as paper mills, refineries, cement plants, copper mines, coal mines, quarries and steel mills, are using this enamel for protection against chemical fumes.

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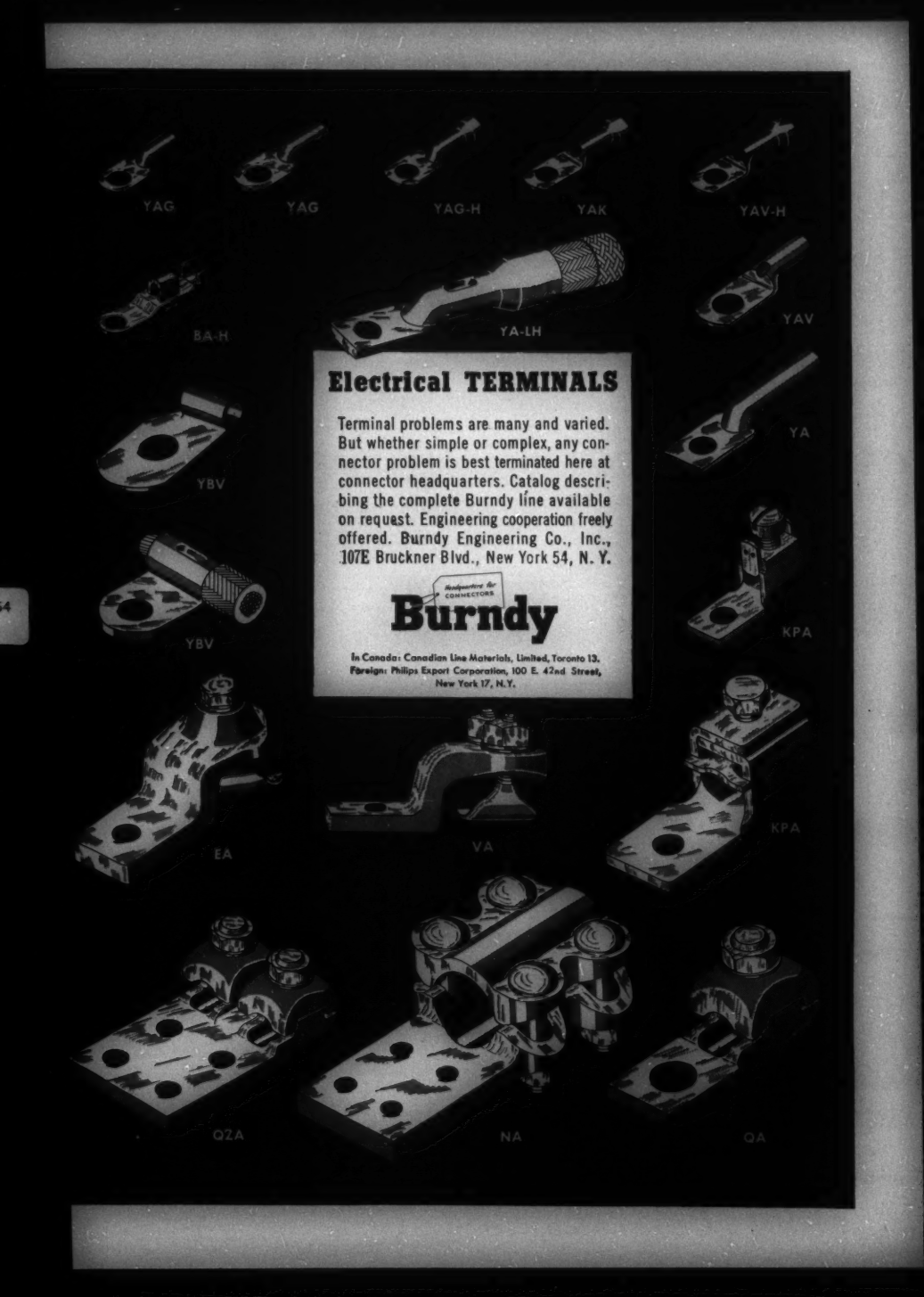

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Terminal problems are many and varied. But whether simple or complex, any connector problem is best terminated here at connector headquarters. Catalog describing the complete Burndy line available on request. Engineering cooperation freely offered. Burndy Engineering Co., Inc., 107E Bruckner Blvd., New York 54, N. Y.

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Burndy

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For postwar, recommend we standardize on Solar's hermetically-sealed, patented special twist-prong-base Type DY electrolytic. They're properly protected against moisture.

E.M.

PART NO.	SOLAR PART NO	CAP'Y MFD	WKG. VOLTS	DIMENSIONS A	DIMENSIONS B
51 B50-1	DY-61	20-20	150	1"	3 3/8
51 B50-2	DY-92	20-20	450	1"	2 1/2
51 B50-3	DY-94	10-10	450	1"	2 1/2
51 B50-4	DY-132	15-10-20	350 350 25	1"	3"
51 B50-5	DY-141	20-10-20	450 450 25	1"	3"

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